



Effect of hydraulic retention time on hydrodynamic behavior of anaerobic-aerobic fixed bed reactor treating cattle slaughterhouse effluent

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ABSTRACT. The study of the hydrodynamic behavior in reactors provides characteristics of the flow regime and its anomalies that can reduce biological processes efficiency due to the decrease of the useful volume and the hydraulic retention time required for the performance of microbial activity. In this study, the hydrodynamic behavior of an anaerobic-aerobic fixed bed reactor, operated with HRT (hydraulic retention time) of 24, 18 and 12 hours, was evaluated in the treatment of raw cattle slaughterhouse wastewater. Polyurethane foam and expanded clay were used as support media for biomass immobilization. Experimental data of pulse type stimulus-response assays were performed with eosin Y and bromophenol blue, and adjusted to the single-parameter theoretical models of dispersion and N-continuous stirred tank reactors in series (N-CSTR). N-CSTR model presented the best adjustment for the HRT and tracers evaluated. RDT (residence time distribution) curves obtained with N-CSTR model in the assays with bromophenol blue resulted in better adjustment compared to the eosin Y. The predominant flow regime in AAFBR (anaerobic aerobic fixed bed reactor) is the N-CSTR in series, as well as the existence of preferential paths and hydraulic short-circuiting.

Keywords: combined system, tracer studies, tailing phenomena, diffusion.

Efeito do tempo de retenção hidráulica no comportamento hidrodinâmico de um reator anaeróbio-aeróbio tratando efluente de abatedouro bovino

RESUMO. O estudo do comportamento hidrodinâmico em reatores fornece as características do regime de vazão e suas anomalias que podem reduzir a eficiência do processo biológico, por meio da diminuição do volume útil e tempo de retenção hidráulica necessária para o desenvolvimento da atividade microbiológica. Neste estudo, foi avaliado o comportamento hidrodinâmico de um reator anaeróbio-aeróbio de leito fixo, operado com TRH (tempo de retenção hidráulica) de 24, 18 e 12 h, no tratamento de efluente bruto de abatedouro bovino. Para a imobilização da biomassa foram utilizados, como meio suporte, espuma de poliuretano e argila expandida. Os dados experimentais dos ensaios estímulo resposta, tipo pulso, foram realizados com eosina Y e azul de bromofenol e ajustados para os modelos de dispersão teóricos uniparamétricos de tanques de mistura completa em série (N-CSTR). O N-CSTR apresentou os melhores ajustes para o TRH e os traçadores avaliados. As curvas DTR (distribuição do tempo de retenção hidráulica) obtidas com o modelo de tanques em série nos ensaios com azul de bromofenol resultaram em melhor ajuste comparado a eosina Y. O regime predominante no RAALF (reator anaeróbio-aeróbio de leito fixo) foi o de mistura completa também como a existência de caminhos preferenciais e curtos-circuitos hidráulicos.

Palavras-chave: sistema combinado, estudo de traçadores, fenômeno de cauda longa, difusão.

Introduction

The challenge of current society, related to sanitation, is to project wastewater treatment systems that are functionally simple, aiming good cost/benefit relation beyond efficiency, to attend the standards established in the current environmental legislation.

Application of combined systems has indicated better utilization of the useful volume, improvement on the performance and stability and higher removal efficiencies of organic matter and nutrients of each process, with the advantages of lesser production of biological sludge and lower costs of implantation and operation when compared

to individual anaerobic systems (Netto & Zaiat, 2012).

Although the studies reported in literature present the advantage of these systems, there is a lack of studies that describe their hydrodynamic behavior. The knowledge of the flow regime of the liquid phase is fundamental to dimension the treatment unities, because the way the fluid flows inside them may influence the velocity of the biological reactions, through changes on the mass transfer rate and on the reactions distribution along the reactor.

As consequence of biomass distribution and biochemical reactions chain, different regions of the reactor present different compositions related to the type of the imposed flow regime. Therefore, the type of flow regime interferes directly in the performance and efficiency of the treatment unit.

In studies with biological reactors applied in the treatment of effluents, the perfect mixing and the plug flow models are mentioned as ideal models. Nevertheless, ideality deviations caused by flow regime phenomenon may occur inside the reactor. Taking into account these ideality deviations, it is possible to obtain a better knowledge of what occurs inside the reactor.

Most part of the biological reactors operating for effluent treatment does not present an ideal hydrodynamic behavior, but can be considered, inside a range of acceptable error, plug flow or complete mixture reactors (Bewtra & Biswas, 2006). The deviations between the real and the ideal regime of flow are caused by hydraulic short-circuiting, recirculation, preferential paths, dead zones and mixtures (Levenspiel, 2000).

According to Fogler (2009), the study of the behavior of non-ideal flow regime in reactors can be described by the concept of residence time distribution (RTD), mixture quality and model applied to describe the system. RTD curves can help in the establishment of flow regimes (plug flow, complete mixture flow or both), determination of the hydrodynamic parameters (real θ , number of reactors in series, dispersion number, tracer recovery and hydraulic efficiency) and identification of flow anomalies inside the reactor. Moreover, RTD curves indicate the long tailing phenomenon that probably occur with the tracer due to its diffusion in the dead zones, adsorption in the biomass or presence of hydraulic short-circuiting in the reactor.

These anomalies may reduce the efficiency of the reactors caused by the decrease of useful volume and hydraulic retention time required to the performance of the microbial activity (Persson,

Somes, & Wong, 1999, Carvalho, Salgado, Passig, & Pires, 2008).

The single-parameter theoretical models of adjustment of the experimental data obtained in hydrodynamic assays are useful to represent the flow regime in the reactor, allowing to compare the curves obtained experimentally to those of the ideal flow model.

Among the evaluation techniques of the hydrodynamic behavior, there is the stimulus-response assay, performed by the addition of a known quantity of inert tracer in the influent, obtaining its concentration in the effluent of the reactor in predetermined time intervals. The tracer addition in the reactor can be performed in pulse, degree, casual or periodic response.

Levenspiel (2000) highlights that with stimulus-response tests is possible to obtain information as hydraulic retention time (θ), hydrodynamic behavior of the reactor by the adjustment of a mathematical model and also to detect anomalies, such as dead zones volume, presence of preferential paths and internal recirculation of the fluid in the reactor.

The novelty and originality of this contribution is related to the combined configuration of this anaerobic-aerobic process in a unique reactor, still poorly reported in the literature. Therefore, this study sought to evaluate the hydrodynamic behavior of an anaerobic-aerobic fixed bed reactor, operated in bench scale, treating raw agro-industrial effluent from cattle slaughterhouse, located at the city of Campo Mourão, in the State of Paraná, Brazil.

Material and methods

The anaerobic-aerobic fixed bed reactor (AAFBR) is constituted of one plexiglass tube of internal diameter of 90 mm, length of 1,000 mm and useful volume of 4.75 L, formed by a feeding chamber and a reaction bed. The reactor (Figure 1) was operated with continuous upflow regime, fed with wastewater collected in the entrance of the settling tank of a cattle slaughterhouse treatment system and kept at room temperature.

The AAFBR feeding was performed by a dosing pump, Provitec® model DM 5000 and the aeration by an air compressor, Boyu® model S2000A, in which the air diffusion was performed through the use of porous stone. The aeration was performed to maintain the dissolved oxygen concentration equal or superior than 2.0 mg L⁻¹.

Cubic matrices of polyurethane foam, with edges of approximately 20 mm, porosity of 95% and bulk density of 26 kg m⁻³ and expanded clay grains with

granulometry varying from 10 to 20 mm were used as support media for biomass immobilization in AAFBR reactor.

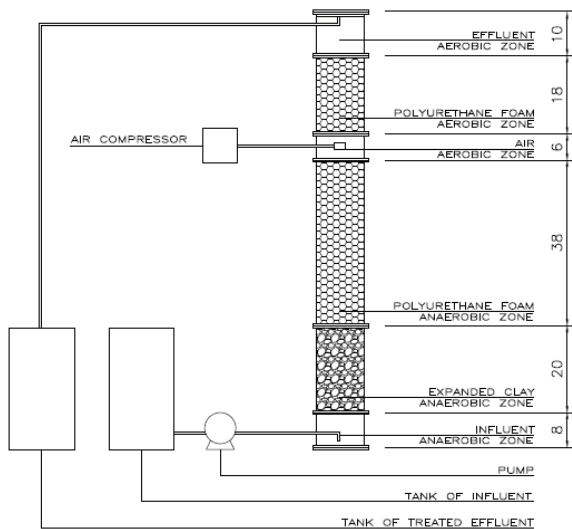


Figure 1. Anaerobic-Aerobic Fixed Bed Reactor (AAFBR).

To evaluate the apparent dynamic equilibrium state, three temporal sampling profiles were performed varying the hydraulic retention time (θ) in 24, 18 and 12 hours, with determination of the physical-chemical parameters pH, alkalinity, chemical oxygen demand (raw and filtered), total solids and total suspended solids of the influent and effluent samples of the reactor according to the methodologies described in American Public Health Association (Apha, 2004), in duplicate. The period of operation for each θ , evaluated was 90 days.

For each θ , tested, three hydrodynamic assays of stimulus-response were carried out in pulse type using eosin Y and bromophenol blue as tracers, with injection volume of 10 mL and injection time of 10 s. The total duration of the assays was of three times the theoretical θ , in which the reactor was submitted, with collection of effluent samples at regular intervals of 45 min. Samples collected were centrifuged for about 2 min at 3,500 rpm in a centrifuge Sislab® model Twister 12T to avoid the interference of solids on absorbance reading by the colorimetric method in a spectrophotometer Hach®

uv-vis, model DR/5000, with wavelength of 516 nm to eosin Y ($691.9 \text{ g g mol}^{-1}$) and 590 nm to bromophenol blue ($669.97 \text{ g g mol}^{-1}$).

Data analyses include the determination of the terms defined in Table 1 according to Levenspiel (2000). The experimental curves of tracer concentration against time were normalized (area under the curve equal to 1), resulting in curves of residence time distribution (E_θ) as function of the dimensionless time (θ). Afterwards, the variance of the response data (σ_θ^2) was calculated for each experiment.

Table 1. Definition of the variables used for obtaining residence time distribution function (E_θ) against dimensionless mean residence time (θ).

Variable	Definition
E_i	C_i/S
S	$\sum C_i \cdot \Delta t_i$
t_R	$\frac{\sum t_i \cdot C_i \cdot \Delta t_i}{\sum C_i \cdot \Delta t_i}$
θ	t/t_R
E_θ	$t_R \cdot E_i$
σ^2	$\frac{\sum t_i^2 \cdot C_i \cdot \Delta t_i}{\sum C_i \cdot \Delta t_i} - t_R^2$
σ_θ^2	σ^2 / t_R^2

Classical single-parameter theoretical models of dispersion of low dispersion (LD), high dispersion (HD) and continuous stirred tanks in series (N-CSTR) were applied to the adjustment of the experimental curves according to Levenspiel (2000) (Table 2).

The dispersion models represent the actual reactor by a tubular-flow reactor in which axial dispersion takes place and the series-of-stirred-tanks (N-CSTR in series) model simulates the reactor by N ideal stirred tanks in series. These characteristics can be verified by the single parameters Peclet number (Pe) for low and high axial dispersion or by the number (N) of ideal stirred tanks in series of N-CSTR in series model. All these parameters were estimated from the variance of the response data presented in Table 2.

Table 2. Single-parameter hydrodynamic theoretical models.

Model	Parameter	Equation
Low Dispersion (LD)	$\sigma_\theta^2 = 2 \left(\frac{D}{u \cdot L} \right)$	$E_\theta = \frac{1}{2\sqrt{\pi(D/u \cdot L)}} \exp \left[-\frac{(1-\theta)^2}{4(D/u \cdot L)} \right]$
High Dispersion (HD)	$\sigma_{\theta,sa}^2 = 2 \left(\frac{D}{u \cdot L} \right) + 8 \left(\frac{D}{u \cdot L} \right)^2$	$E_{\theta,sa} = \frac{1}{2\sqrt{\pi(D/u \cdot L)}} \exp \left[-\frac{(1-\theta)^2}{4\theta(D/u \cdot L)} \right]$
N-CSTR in series	$N = \frac{1}{\sigma_\theta^2} = \frac{\bar{\theta}^2}{\sigma^2}$	$E_\theta = \frac{N(N \cdot \theta)^{N-1}}{(N-1)!} e^{-N \cdot \theta}$

The volume of dead zones was calculated according to the methodology reported by Peña, Mara, and Avella (2006) based on the value of real θ obtained from hydrodynamic assays and the total volume of the reactor. The presence of hydraulic short-circuiting was verified by the relation between the time of the first appearance of tracer in the effluent (peak) and the theoretical hydraulic retention time (θ_t) in the effluent of the reactor in accordance with the methodology adapted by Sarathai, Koottatep, and Morel (2010). The theoretical hydraulic retention time (θ_t) was calculated as V/Q , where, V is the volume of slaughterhouse effluent in the reactor and Q is the flow rate (Levenspiel, 2000, Fogler, 2009).

The hydraulic efficiency was obtained by the product of the effective volume ratio and the number of continuous stirred tanks in series, according to the methodology reported by Persson et al. (1999) and Sarathai et al. (2010). These authors considered that the hydraulic efficiency may be categorized into the following three groups: (i) good hydraulic efficiency with $\lambda > 0.75$; ii) satisfactory hydraulic efficiency with $0.5 < \lambda \leq 0.75$; and (iii) poor hydraulic efficiency where $\lambda \leq 0.5$.

Results and discussion

AAFBR monitoring

Results of the physical-chemical analysis for the influent and effluent samples obtained during the operation of the AARFB, submitted to θ_t of 24, 18 and 12 hours were satisfactory, with higher values of alkalinity in the effluent (1,000 mg $\text{CaCO}_3 \text{ L}^{-1}$) than in the influent (600 mg $\text{CaCO}_3 \text{ L}^{-1}$), indicating its buffering capacity. Regarding to the organic matter, average removal efficiencies, and their respective standard deviations, of raw COD_{influent} were of 57 (COD = 1,526 [59] mg L^{-1}), 70 (COD = 3,350 [82] mg L^{-1}) and 71% (COD = 3,396 [97] mg L^{-1}), respectively; filtered COD_{influent} - 70 (COD = 794 [39] mg L^{-1}), 72 (COD = 974 [68] mg L^{-1}) and 71% (COD = 982 [81] mg L^{-1}), respectively.

Similar behavior was observed by Kreutz, Passig, Carvalho, Mees, and Gomes (2014) that verified 59% of organic matter removal in the same configuration of the reactor treating raw cattle slaughterhouse effluent; and Abreu and Zaiat (2008) that obtained removal of 37% to COD when an anaerobic-aerobic reactor was operated with θ_t of 8 hours, increasing to 46% when the θ_t was reduced to 6 hours in the treatment of sewage.

The average removal efficiencies, and their respective standard deviations, to total solids (TS) and total suspended solids (TSS) were of 74

(TS = 2,742 [83] mg L^{-1}) and 92% (TSS = 1,630 [64] mg L^{-1}) for θ_t of 24 hours, 89 (TS = 4,652 [91] mg L^{-1}) and 88% (TSS = 1,463 [47] mg L^{-1}) for θ_t of 18 hours and 73 (TS = 6,396 [94] mg L^{-1}) and 92% (TSS = 2,133 [69] mg L^{-1}) for θ_t of 12 hours.

Hydrodynamic assays

The experimental curves of residence time distribution (RTD) obtained with the adjustment of the single-parameter theoretical models are represented in Figure 2 for each tracer individually.

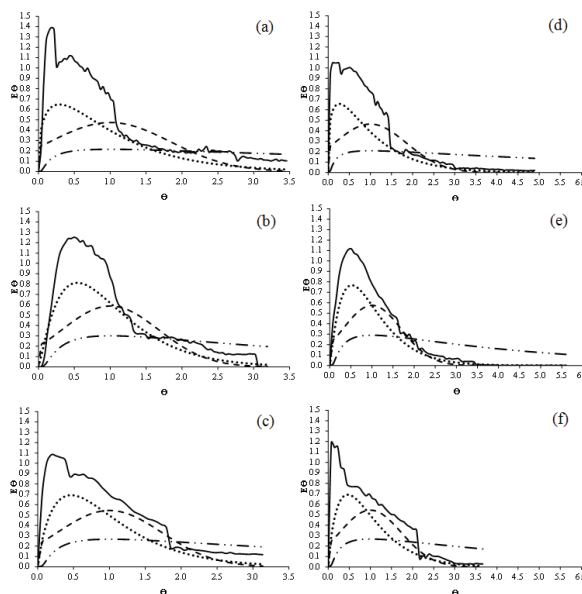


Figure 2. Individual results of RTD curves obtained experimentally utilizing the tracers: Eosin Y (a) θ_t 24 hours; (b) θ_t 18 hours; (c) θ_t 12 hours; bromophenol blue (d) θ_t 24 hours; (e) θ_t 18 hours; (f) θ_t 12 hours.

Sharp peaks at the first hours of the assays carried out with θ_t of 18 and 12 hours can be observed in RTD curves, for both tracers tested, and also with θ_t of 24 hours with bromophenol blue, that probably indicate the existence of preferential paths inside the reactor. Méndez-Romero, López-López, Vallejo-Rodríguez, and León-Becerril (2011) concluded that the peak of initial concentration, followed by exponential decay of the tracer concentration is a typical behavior of upflow anaerobic fixed bed reactors used in the treatment of slaughterhouse effluents.

Méndez-Romero et al. (2011) also observed long tails in RTD curves and pointed out that the proximity of these two events, in other words, the moment that the tracer appears for the first time in the effluent and the point that the maximum concentration in the exit is registered, suggests that a portion of the fluid moves through short-circuiting

formed inside the porous medium, reducing the useful volume of the reactor.

Tailing phenomenon was observed in the RTD curves obtained from the hydrodynamic assays, indicating the slow decay of the tracer concentration at the exit of the reactor. Jimenez, Noyola, Capdeville, Roustan, and Faup (1988) defined tailing as the tracer release from the pores of the support media once the tracer pulse has passed.

Carvalho et al. (2008) attributed the long tailing phenomenon to the diffusion of the tracer eosin Y in dead zones and its slow release in the effluent of a UASB reactor (160 L) applied in the treatment of sewage. Kreutz et al. (2014) also observed the long tail effect in an anaerobic-aerobic combined reactor, treating cattle slaughterhouse wastewater, and attributed this phenomenon to the adsorption of eosin Y in the support medium utilized for biomass immobilization. Levenspiel (2000) noticed that the long tail is related to some hydrodynamics aspects such as the tracer diffusion in dead zones of the reactor, tracer adsorption in the biomass of the reactor or the presence of hydraulic short-circuiting.

In the assays with bromophenol blue, the long tailing phenomenon is less evident because is released faster than eosin Y, which probably remains adsorbed in the support medium, being discharged slowly in the effluent of the reactor. Long tailing phenomenon was also verified by Bernardez, Lima, and Almeida (2008) operating a cylindrical reactor filled with glass pearls; Capela et al. (2009) treating effluents of gas condenser without immobilized biomass; Lourenço and Campos (2009) evaluating a

UASB reactor fed with wastewater of swine confinement; Méndez-Romero et al. (2011) operating an upflow anaerobic fixed bed reactor, immobilized with volcanic stones; Ji, Zheng, Xing, and Zheng (2012) investigating a compartmentalized reactor in hydrodynamic assays using hydrochloric acid, lithium, lithium chloride and rhodamine B as tracers, respectively.

Different response curves for the different tracers used are noticed in Figure 2, even with the reactor operated in similar operational conditions. De Nardi, Zaiat, and Foresti (1999) pointed out that each tracer can provide different hydrodynamic responses and the interpretation of the characteristics of the flow type depend on the chosen tracer to evaluate the hydrodynamic behavior of the fluid inside the reactor.

The results of the hydrodynamic parameters, obtained experimentally from the residence distribution time (RTD) curves, after the adjustment by the single-parameter theoretical models, are shown in Table 3.

Analyzing the results presented in Table 3, a delay of approximately 15, 9 and 4% in the response of eosin Y was observed to the theoretical θ_t of 24, 18 and 12 hours, respectively. This delay may be attributed to the diffusion of the tracer in the dead zones or its adsorption in the polyurethane foam, used as support material for the biomass and, consequently, to its slow release. However, adsorption is not likely to occur on biomass due to the anionic nature of the tracers used in this study, as reported by Jimenez et al. (1988).

Table 3. Parameters, correlation coefficients and anomalies obtained for the adjustment of the theoretical models to experimental curves obtained for each experiment in AAFBR reactor.

Tracer	Assay	$\frac{\theta_t}{\theta_r}$ (hour)		N-CSTR (N)	LD (D uL ⁻¹)	HD (D uL ⁻¹)	Correlation coefficient (R ²)			Peak (hour)	V _d (L)	Ψ	λ
							N-CSTR	LD	HD				
EY	1	21.5		2	0.349	1.674	0.947	0.561	0.108	3.8	0.7	0.2	0.2
	2	24	30.4	2	0.159	0.52	0.976	0.796	0.528	19.5	-1.8	0.6	1.4
	3		31.5	3	0.151	0.485	0.962	0.758	0.471	21.8	2.1	0.7	2.1
Bb	1	15		1	0.377	1.888	0.986	0.806	0.156	3.8	2.5	0.3	0.4
	2	24	14.3	1	0.388	1.98	0.971	0.781	0.071	1.5	2.7	0.1	0.4
	3		14.2	2	0.313	1.407	0.958	0.807	0.442	6	2.7	0.4	0.5
EY	1	18.5		2	0.26	1.06	0.982	0.806	0.321	7.5	-0.2	0.4	0.6
	2	18	19.6	2	0.254	1.027	0.959	0.729	0.318	9	-0.6	0.5	0.8
	3		20.7	2	0.259	1.054	0.934	0.69	0.164	7.5	-1	0.4	1
Bb	1	10.6		2	0.246	0.975	0.985	0.929	0.634	5.3	2.8	0.5	0.6
	2	18	10.9	2	0.287	1.233	0.997	0.889	0.542	5.3	2.6	0.5	0.5
	3		9.4	1	0.495	2.954	0.99	0.792	0.314	1.5	3.2	0.2	0.2
EY	1	10.8		2	0.32	1.457	0.959	0.815	0.356	1.5	0.7	0.1	0.2
	2	12	11.9	2	0.268	1.11	0.974	0.873	0.463	2.3	0.1	0.2	0.5
	3		14.7	2	0.222	0.839	0.915	0.762	0.486	4.5	-1.5	0.3	1.3
Bb	1	10.3		2	0.273	0.142	0.935	0.868	0.465	0.7	0.9	0.1	0.1
	2	12	7.9	2	0.316	1.434	0.977	0.842	0.508	1.5	2.3	0.2	0.4
	3		15.1	3	0.205	0.746	0.904	0.884	0.474	1.5	-1.7	0.1	1.8

Legend: EY = Eosin Y; BB = Bromophenol blue; θ_t = theoretical hydraulic retention time; θ_r = real hydraulic retention time; N-CSTR (N) = number of reactors; LD = low dispersion; HD = high dispersion; D uL⁻¹ = dispersion number; V_d = volume of dead zones; Ψ = hydraulic short-circuiting; λ = hydraulic efficiency.

Similar behavior related to the delay in the response of tracers was previously reported in the literature. Calheiros, Perico, and Nunes (2009) observed a delay of approximately 4% in the response of sodium chloride (NaCl) of a sequential anaerobic reactor (862,37 L), revealing the existence of hydraulic short-circuiting. Carvalho et al. (2008) assigned a delay in the response of eosin Y to the presence of dead zones in a UASB reactor of 160 L, in addition of a possible adsorption of the tracer in the biomass. Escudié, Conte, Steyer, and Delgenès (2005) noted a late effect in the response of eosin Y and mentioned that the delay may perform a significant role in the determination of the residence time of an anaerobic fixed bed reactor (948 L). These authors noticed an increase of the dispersion number of low and high intensity with the decrease of the flow rate from 50 to 15 L hour⁻¹, as observed in this study for each tracer (Table 3).

The hydrodynamic assays carried out with bromophenol blue presented advance in the tracer response of approximately 40, 43 and 7% of the real θ_r regarding the theoretical θ_t of 24, 18 and 12 hours, respectively. Borges, Matos, Calijuri, Oliveira, and Roldão (2009) verified that the dye utilized in the assay influences the results of the hydraulic and hydrodynamic parameters when determining the RTD curves of a wetland system, using rhodamine WT and sodium fluorescein as tracers. The authors noticed values of peaks of concentration lower than the theoretical θ on RTD curves and assigned this behavior to the formation of preferential paths and occurrence of stagnation regions inside the reactor.

Levenspiel (2000) confirms that when the dispersion number tilts to the infinite ($D \mu L^{-1} = \infty$), the flow behavior tilts to a perfectly mixing system, whereas, when the dispersion number is equal to zero ($D \mu L^{-1} = 0$), it refers to an ideal plug flow system. The author also defines that $D \mu L^{-1}$ in the range of 0.000-0.002 indicates dispersion of low intensity, $D \mu L^{-1}$ in the range of 0.002-0.025 indicates dispersion of medium intensity and $D \mu L^{-1}$ in the range of 0.025-0.200 means that the model tilts to dispersion of high intensity.

The average values of dispersion were 0.220; 0.258 and 0.270 with eosin Y and 0.359, 0.343 and 0.265 with bromophenol blue to the low dispersion model; 0.893; 1.047 and 1.135 with eosin Y and 1.758; 1.721 and 0.774 with bromophenol blue to the high dispersion model to the assays with θ_t of 24, 18 and 12 hours, respectively.

For the continuous stirred tanks in series model (N-CSTR), the numbers resulted in 2 reactors to the assays with eosin Y and 1 and 2 reactors with bromophenol blue to θ_t of 24, 18 and 12 hours,

respectively. Therefore, the higher are the $D \mu L^{-1}$ values, the greater will be the dispersion, indicating that the dispersed flow tilts to the perfect mixing system proved in this study by the values of R^2 of 0.962; 0.958 and 0.949 with eosin Y and 0.972; 0.991 and 0.939 with bromophenol blue to θ_t of 24, 18 and 12 hours, respectively.

De Nardi et al. (1999) obtained 3 and 6 continuous stirred reactors in series (N-CSTR) to the assays performed with eosin Y and bromophenol blue in a horizontal-flow anaerobic immobilized sludge reactor (1.99 L) operated with θ_t of 24 hours treating sewage. Observing the data of the correlation coefficients in Table 3, it is possible to confirm that the N-CSTR model adjusted better the experimental data with 2 continuous stirred reactors in series, independently of the hydraulic load and the tracer used and the R^2 of 0.962, 0.958 and 0.949 with eosin Y and 0.972, 0.991 and 0.939 with bromophenol blue to θ_t of 24, 18 and 12 hours, respectively, corroborated the statement of the authors mentioned above.

Anomalies on hydrodynamic behavior

The results of the volume of dead zones, presence of hydraulic short-circuiting and hydraulic efficiency, obtained from the results of stimulus-response hydrodynamic assays carried out in the AARFB reactor to θ_t of 24, 18 and 12 hours are also presented in Table 3.

Negative values to the volume of dead zones (V_d) in the assays carried out with eosin Y and bromophenol blue are noted in Table 3. According to Qian et al. (2006), these results indicate that the volume of dead zones is too little that can be considered negligible. Peña et al. (2006) noticed negative values in their assays and pointed out that as smaller as the volume of dead zones, closest is the flow regime to a perfect mixing system, provided by the increase of the upflow rate of the liquid.

The same behavior was observed in this study with the decrease of the dead volumes provided by the increase of the hydraulic load in the assays with eosin Y from 24 to 18 hours (V_d of 0.7 L) and bromophenol blue from 18 to 12 hours (V_d of 1.6 L) and 24 to 12 hours (V_d of 1.9 L).

Another hydrodynamic aspect observed is that the lower the θ_r obtained regarding the θ_t , the greater the volume of dead zones. This was noted in the assays with eosin Y (θ_t 24 and θ_r 21.5 hours) and bromophenol blue (θ_t 18 and θ_r 9.4 hours) in which the volume of dead zones resulted in 2.5 and 3.2 L, respectively.

According to Sarathai et al. (2010), the presence of hydraulic short-circuiting is verified when $\Psi \leq$

0.3. The results presented in Table 3 indicate that this deviation of the ideality was observed only in the assays with bromophenol blue to θ_t of 24 and 12 hours.

The hydraulic short-circuiting phenomenon can be assigned when the θ_r is lower than the θ_t . Ahnert, Kuehn, and Krebs (2010) confirmed that the higher the θ applied, the lesser the probability of short-circuiting appearance. Moreover these authors stated that the later the appearance of the tracer concentration peak, the sharper the response curve and, therefore, hydraulic short-circuiting and dead zones will not be noted.

The assays carried out with eosin Y presented good hydraulic efficiency ($\lambda \geq 0.75$) with average values of 1.2 and 0.8% to θ_t of 24 and 18 hours, respectively. These results were higher than those obtained in assays with bromophenol blue that resulted in lower hydraulic efficiency to the θ_t tested.

Conclusion

RTD curves and the single-parameter models adjustment indicate that the perfect mixing represents satisfactorily the flow regime in the AARFB reactor. Dispersion number was higher in LD and HD models, demonstrating longitudinal dispersion of the fluid and high mixture degree in the reactor.

Ideality deviations observed by the delay of eosin Y and advance of bromophenol blue show the presence of hydraulic short-circuiting and dead zones inside the reactor, resulting in a decrease of the hydraulic efficiency.

The hydrodynamic behavior of the reactor was better described by the operational condition of 24 hours to θ_t with eosin Y as tracer.

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References

- Abreu, S. B., & Zaiat, M. (2008). Desempenho de reator anaeróbio-aeróbio de leito fixo no tratamento de esgoto sanitário. *Engenharia Sanitária e Ambiental*, 13(2), 181-188.
- Ahnert, M., Kuehn, V., & Krebs, P. (2010). Temperature as an alternative tracer for the determination of the mixing characteristics in wastewater treatment plants. *Water Research*, 44(6), 1765-1776.
- American Public Health Association. (2004). *Standard methods for the examination of water and wastewater*. Washington, DC: Apha.
- Bernardez, L. A., Lima, L. R. P. A., & Almeida, P. F. (2008). The hydrodynamics of an upflow packed-bed bioreactor at low Reynolds number. *Brazilian Journal of Petroleum and Gas*, 2(3), 114-121.
- Bewtra, J. K., & Biswas, N. (2006). *Biological treatment of wastewater. Encyclopedia of environmental science and engineering*. Boca Raton, FL: CRC Press.
- Borges, A. C., Matos, A. T., Calijuri, M. C., Oliveira, G. H. H., & Roldão, J. S. F. (2009). Uso de traçadores para avaliação da hidrodinâmica de sistemas alagados construídos operando sob condições climáticas tropicais. *Engenharia Agrícola*, 29(2), 301-310.
- Calheiros, H. C., Perico, A. S., & Nunes, C. F. (2009). Estudo experimental de aspectos hidrodinâmicos e da partida de um reator anaeróbio sequencial tratando esgotos domésticos. *Ambiente & Água*, 4(3), 144-156.
- Capela, I., Bilé, M. J., Silva, F., Nadais, H., Prates, A., & Arroja, L. (2009). Hydrodynamic behaviour of a full-scale anaerobic contact reactor using residence time distribution technique. *Journal of Chemical Technology and Biotechnology*, 84(5), 716-724.
- Carvalho, K. Q., Salgado, M. T., Passig, F. H., & Pires, E. C. (2008). Avaliação hidrodinâmica de reator UASB submetido à variação cíclica de vazão. *Engenharia Sanitária e Ambiental*, 13(2), 226-235.
- De Nardi, I. R., Zaiat, M., & Foresti, E. (1999). Influence of the tracer characteristics on hydrodynamic models of packed-bed bioreactors. *Bioprocess Engineering*, 21(5), 469-476.
- Escudié, R., Conte, T., Steyer, J. P., & Delgenès, J. P. (2005). Hydrodynamic and biokinetic models of an anaerobic fixed-bed reactor. *Process Biochemistry*, 40(7), 2311-2323.
- Fogler, S. H. (2009). *Elementos de engenharia das reações químicas*. São Paulo, SP: LTC.
- Ji, J., Zheng, K., Xing, Y., & Zheng, P. (2012). Hydraulic characteristics and their effects on working performance of compartmentalized anaerobic reactor. *Bioresource Technology*, 116(7), 47-52.
- Jimenez, B., Noyola, A., Capdeville, B., Roustan, M., & Faup, G. (1988). Dextran blue colorant as a reliable tracer in submerged filters. *Water Research*, 22(1), 1253-1257.
- Kreutz, C., Passig, F. H., Carvalho, K. Q., Mees, J. B. R., & Gomes, S. D. (2014). Performance of an anaerobic-aerobic reactor and kinetic study of organic matter removal of cattle slaughterhouse effluent. *Revista Engenharia Agrícola*, 34(2), 341-351.
- Levenspiel, O. (2000). *Engenharia das reações químicas*. São Paulo, SP: Edgard Blücher Ltda.
- Lourenço, A. M. P., & Campos, C. M. M. (2009). Hydrodynamic behavior of a lab-scale upflow anaerobic sludge blanket reactor (UASB) operated with an adopted hydraulic retention time (HRT) of 12 hours. *Ciência e Agrotecnologia*, 33(4), 1139-1144.
- Méndez-Romero, D. C., López-López, A., Vallejo-Rodríguez, R., & León-Becerril, E. (2011). Hydrodynamic and kinetic assessment of an anaerobic

- fixed-bed reactor for slaughterhouse wastewater treatment. *Chemical Engineering and Processing: Process Intensification*, 50(3), 273-280.
- Netto, A. P. O., & Zaiat, M. (2012). Treatment of domestic sewage in an anaerobic-aerobic fixed-bed reactor with recirculation of the liquid phase. *Clean - Soil, Air, Water*, 40(9), 965-971.
- Peña, M. R., Mara, D. D., & Avella, G. P. (2006). Dispersion and treatment performance analysis of an UASB reactor under different hydraulic loading rates. *Water Research*, 50(3), 445-452.
- Persson, J., Somes, N. L. G., & Wong, T. H. F. (1999). Hydraulics and science of constructed wetlands and ponds. *Water Science and Technology*, 40(3), 291-300.
- Qian, T., Wang, X. P., & Sheng, P. (2006). A variational approach to moving contact line hydrodynamics. *Journal of Fluid Mechanics*, 564(4), 333-360.
- Sarathai, Y., Koottatep, T., & Morel, A. (2010). Hydraulic characteristics of an anaerobic baffled reactor as onsite wastewater treatment system. *Journal of Environmental Sciences*, 22(9), 1319-1326.

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