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Evaluation of Hydraulic Performance of a Biological Filter Using Seashells as Support Material

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Abstract

This research evaluated the hydraulic behaviour of a biological filter (BF) that used marine shells as support material for the post-treatment of municipal wastewater (MWW). The BF was theoretically designed with ascendant-descendent flow to describe a piston flow. The hydraulic evaluation was carried out in the liquid phase and in operation using Li^+ (LiCl) as liner applied instantly in the affluent in a 6.43 hours theoretical hydraulic retention time (THRt). The analysis of the distribution of residence times allowed to determine that the flow pattern in the filter has a piston flow tendency, which was corroborated with a 0.145 and a 0.08 dispersion, a piston fraction of 0.916 and 0.839 with tap water and in operation respectively. The support material increased the piston flow's behavior, as a consequence of the reduction of the mixture there was a small fraction of stagnant zone. (0.012).

Keywords: dual camera reactor, coefficient of dispersion, hydraulic efficiency, dead zones

1 Introduction

The biological filter (BF) are fixed-bed reactors, used to reduce the dissolved organic material in the wastewater (WW) with the help of micro-organisms that are found on the surface of the support material (SM). The SM that is deposited in the BF consists of solid media that have high porosity and diversity in their geometry. The microorganisms adhere on the surface of these, creating a biological film to efficiently eliminate the pollutant [1]. The WW provides the substrate for the bacteria that are attached to these porous media, making these particularly robust to the hydraulic variations and to the variations of organic charge [2]. With the features of the high adaptability to the WW, the underproduction of mud, the easy maintenance and the energy saving, the BF is extensively used for the treatment of WW.

The removal of organic load of the WW in a BF involves biochemical processes and hydraulic aspects such as the flow characteristics, the mixing regime, the times of residence, the reactor geometry, on the other hand the conditions of non-ideal flow such as short circuits, dead zones and internal recirculation affect its performance [3]. Hydraulics and the mixing degree occurring within a BF strongly influence the contact between the substrate and the bacteria, which is related to the number of microorganisms present and their performance by removing contaminants present in the substrate. Therefore the knowledge of the hydraulic aspects that develop within the BF is important.

The hydraulic behavior of a BF can be determined through a test of impulse markers and calculating the residence time distribution (RTD) curves at different flow rates. Although normally the hydraulic retention time (HRT) is evaluated as a fundamental parameter for the design and operation of reactors [4], instead of using the HRT, the real flow conditions in a filter, are better defined by using the residence time distribution (RTD) and the HRT obtained from tests of experimental tracers [5].

This research assesses the hydraulic conditions of a BF using Li^+ (LiCl) as liner, this was done under two conditions: a liquid phase using only tap water and one in operation fueling the BF with municipal wastewater (MWW) highlighting the configuration and the layout of the BF, which is connected to an integrated serial system by an anaerobic reactor dual camera and a aeration tower (AT). The BF acts as final component and post-treatment unit. Under this evaluation, the curiosity to check the type of hydraulic regime that the system presents towards the designed theoretical (piston flow) is born, as well as the influence of the filtering medium, the chambers or baffles on the hydraulic behavior that describe an ascendant-descendent flow.

2 Materials and methods

Experimental unit. The studied system corresponds to a BF at pilot scale, which was manufactured in transparent acrilic with dimensions of 70.5 cm wide, 60 cm high and 121.5 cm deep; a total capacity of 530 l and useful of 460 L distributed in 5 chambers divided by bafles (separation every 33.3 cm) that propitiated an ascendant and descendant flow; to maximize the contact with the support material (SM) and the liquid volume of the BF. The SM was marine shells (*Arca zebra*), from the shores of the Colombian Guajira, approximately 44,000 shells with an effective volume of 70 L.

The BF was part of a serial treatment unit, consisting of an anaerobic reactor dual camera that delivered its effluent to a tower of aeration (TA) system and finally to the BF object of this investigation. The MWW was sucked from a collector; a self- priming peripheral pump 1HP was used, and it was equipped with a time programmer of 10 events that fed a tank of 1200 L each 2.4 h. A peristaltic pump of 6-600 rpm was used to feed the system. The Figure 1 shows a scheme of the experiment.

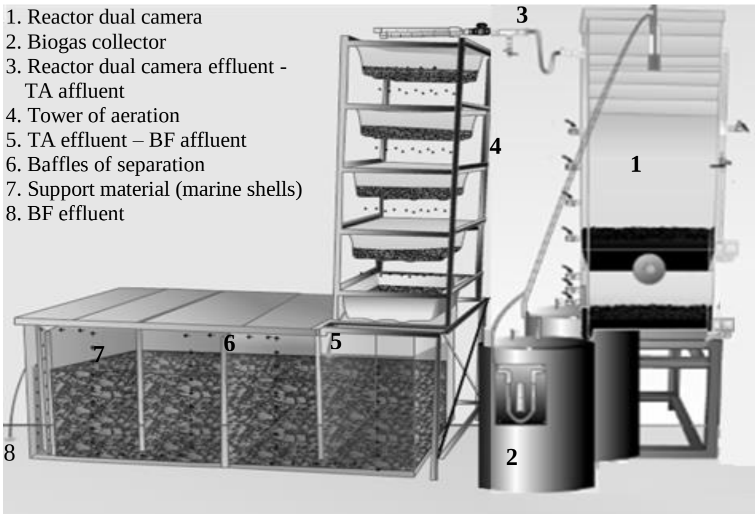

Figure 1. Scheme of the experimental unit

Support material characterization. To calculate the surface and the adhesion area of the marine shells (*Arca zebra*), the formula of the surface area for ellipsoidal objects was applied, and it was calculated according to the equations 1 and 2.

$$S \approx 4\pi(a^p b^p + a^p c^p + b^p c^p/3)^{1/p} \quad (1) \qquad c = \sqrt{a^2 - b^2} \quad (2)$$

Where p ≈ 1.6075, is the relative error. With this expression a maximum error of ±1. 061% is got, depending on the values of a, b and c, being these the semi-axes measured with a vernier (0-150 mm).

Start-up and operation of the BF. The marine shells were placed within the BF for the development of the microbial film on the support material, the BF was fed with raw MWW for twenty (20) days and it worked for charges for a period of three days. Attached the microbial film to the shells, the serial system (the anaerobic reactor dual camera and the aeration Tower) was connected, the pH, the total carbonic alkalinity and the temperature in the influent and effluent of the BF were daily measured. The BF operation was conducted in times of theoretical hydraulic retention of 12.85; 10.71; 8-57 and 6.43 h, by 207 days, in which the following parameters were determined: temperature, pH, alkalinity, BOD, total and soluble COD, following the established in the Standard Methods [6].

Hydraulic evaluation. To assess the hydraulic behaviour of the BF, the THR of 6.43 h was taken, for the hydraulic evaluation a liner was applied in a punctual manner, first using only tap water and then in operation with support material and trying the MWW. The volume considered under operating conditions is the liquid volumen (subtracted from the total volume occupied by the material support). Lithium was used as liner (Li^+) in the form of (LiCl) for being an element of little interaction, for being non-toxic and also because it is not absorbed by the micro-organisms [7]. A volume of 250 ml with a concentration of 5000 mgLi^+/litre (C_0 = 2.5 mg/L) was injected. The measurements of lithium were conducted in an atomic absorption spectrophotometer (Perkin Elmer mark, model 3110, method of acetylene- air gas flame to 670.80 nm) with a minimum detection limit of 0.01 mg/L. The samples were preserved and treated according to standard methods [6].

For the hydraulic analysis the number of dispersion (d) was calculated by the methods small extent of dispersion (SED), large extend of dispersion open vessel (LEDov), large extent of dispersion closed vessel (LEDcv) using the equations 3-5 respectively proposed by [8], the tanks-in-series (TS) proposed by [9] and small extend of dispersion closed-open vessel (SEDcov) proposed by [10] according to the equations 6 and 7 respectively. Equations 8 and 9 were used to calculate the THR by traditional methods [8].

$$\Sigma_\theta^2 = 2d \quad (3)$$

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} = 2d + 8d^2 \quad (4)$$

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} = 2d - 2d^2\left[1 - e^{-\left(\frac{1}{d}\right)}\right] \quad (5)$$

$$d = \frac{1}{2(N-1)} \quad (6)$$

$$\sigma_\theta^2 = 2d + 3d^2 \quad (7)$$

$$\sigma^2 = \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2 \quad (8)$$

$$\bar{t} = \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \quad (9)$$

Where: σ_θ^2 = Non-dimensional variance of the distribution curve of the liner, θ= dimensionless sampling time, e = base of the natural logarithms = 2.718 (dimensionless), d= number or module of dispersion (dimensionless), $\bar{t}$ =HRT = hydraulic retention time (min), N = number of tanks-in-series (dimensionless), C_i = concentration of the tracer in the effluent over time t_i (mg/L).

To check the fitting quality of the experimental data of concentration of the tracer, models small extent of dispersion (SED), large extend of dispersion open vessel (LEDov) and tanks-in-series were used (ST) proposed by [8] and the dispersion model proposed by [11] according to the equations 10-13 respectively.

$$E_\theta = \frac{1}{2\sqrt{\pi d}} e^{\left[-\frac{(1-\theta)^2}{4d}\right]} \quad (10) \qquad E_\theta = \frac{1}{2\sqrt{\pi \theta d}} e^{\left[-\frac{(1-\theta)^2}{4\theta d}\right]} \quad (11)$$

$$E_\theta = \frac{N(N\theta)^{N-1}}{(N-1)!} e^{-N\theta} \quad (12) \qquad C(x,t) = \frac{M}{V} \frac{1}{\sqrt{4\pi \frac{D}{vx}\left(\frac{t}{\bar{t}}\right)^3}} e\left[-\frac{\left(1-\frac{t}{\bar{t}}\right)^2}{4\frac{D\,t}{vx\bar{t}}}\right] \quad (13)$$

Where: $C(x,t)$= the concentration of the tracer to a distance x (m) and a time t (mg/L). v= linear velocity (m/h), t = time elapsed since the injection of the tracer to the sampling, E(θ) = exit-age distribution function of the tracer (dimensionless) liner, σ^2=variance of the curve of the liner (min^2), σ_θ^2= Non-dimensional variance of the distribution curve of the tracer, M = mass of the added liner (g), reactor's volume, x = distance in the reactor (m). To determine the hydraulic pattern of the BF: hydraulic efficiency (β), fraction of plug volume (I_p), dead volume (I_d), mixed volume (I_m) the equations 14-17 were used [12].

$$\beta = \frac{\bar{t}}{t_o} \quad (14) \qquad I_p = \frac{V_p}{V} = \frac{\theta_{max}}{\bar{\theta}} \quad (15)$$

$$I_d = \frac{V_d}{V} = 1 - \beta \quad (16) \qquad I_M = \frac{V_M}{V} = 1 - \frac{V_p}{V} - \frac{V_d}{V} \quad (17)$$

Where: V = reactor volume (L), V_p= volume plug-flow (L), V_d= dead volume (L), θ_{max}= Dimensionless time for maximum concentration, $\bar{\theta}$ = Dimensionless hydraulic retention time.

3. Results and discussion

Characterization of the support material and start-up of the BF. In the calculation of the surface area of the MS (marine shells; *Arca zebra*), it was obtained that the arithmetic average and the height, length and width standard deviations were of 1.46 ± 0.36; 4.60 ± 0.71 and 1.90 ± 0.31, respectively. The average surface area by shells was 25.7 cm^2/shell for an estimate of 1.130.800 cm^2 for the 44,000 shells that occupied a volume of 70 L in BF.

Hydraulic evaluation. The Figure 2 presents the comparison and fitting of the model to the experimental data of the RDT. The peaks that show presence of advective flow were not observed in none of the cases. In both tested conditions the BF showed a typical delay of plug-flow (the liner starts to leave after a certain time), therefore the early output of the liner did not occur. Analyzing the distribution of the RTD it can be said that dead zones did not appear in the liquid phase (Figure 2a), which did occurred in operation (Figure 2b) where $E\theta_{max} > 1$. The dead zones cause that THR > THRt (real hydraulic retention time less than the theoretical) the hydraulic efficiency of the system decreases [12][13]. The shape of the curves in Figure 2 is the typical of a dispersed flow where there is the presence of plug-flow and mixture.

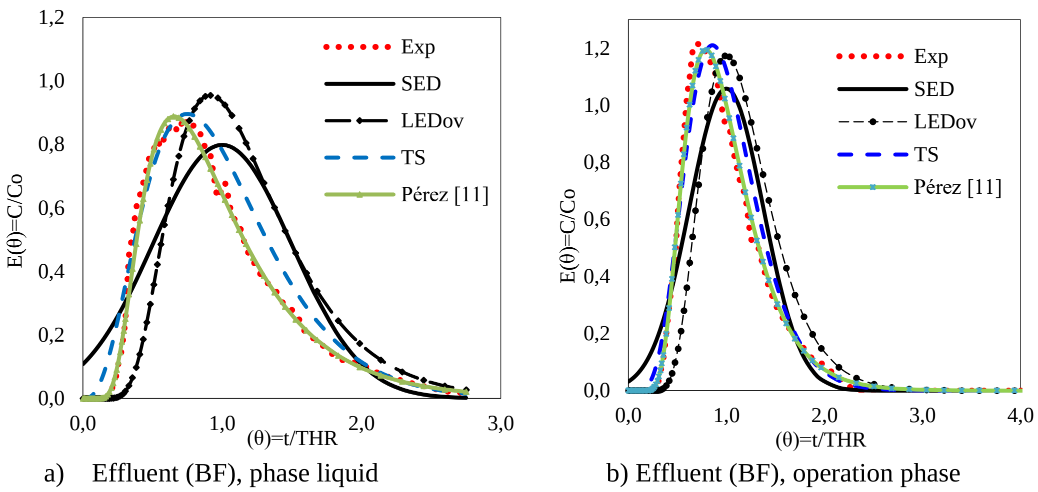

Figure 2. Distribution and fitting experimental data of the tracer output.

In Table 1, it can be observed that the experimental data showed a better fitting to the proposed model by [11], which can be observed in the Figure 2, this model showed the minor errors and although the coefficient of determination does not measure the degree of error, it is an indicator of the explanation of the model data and it suggests the association that exists between the measured and the simulated data in an indirect way. The tanks-in-series model showed a good fitting as it has happened in other researches [14], but the errors were far superior to those obtained by [11]. So onwards we will take the information of this model for the analysis and for the discussion of the results.

Table 1. Kindness of the fitting of the experimental to the dispersion models

Levenspiel Model, 1999									Pérez [11]		
SED			LEDov			ST					
R^2	SSE	RMSE	R^2	SSE	RMSE	R^2	SSE	RMSE	R^2	SSE	RMSE
Liquid phase											
0.867	2.379	0.178	0.808	3.287	0.209	0.979	0.484	0.080	0.996	0.0363	0.0225
In operation											
0.917	2.275	0.174	0.891	2.924	0.197	0.982	0.541	0.085	0.997	0.0410	0.0226

R^2: determination coefficient, SSE: sum of squared errors, RMSE: root mean squared error

The Table 2 presents a summary of the dispersion numbers obtained by the different methods and the THR. According to the number of dispersion, the following behavior flow ($d \leq 0.25$) was recorded in the liquid phase (d= 0.145), and in the operation (d = 0.08). Our highest values were obtained in anaerobic filters of 7.5 m^3 using different support media and finding dispersion numbers 0.365-0.380, concluding that there was mixed flow when d >0.2 [15] was obtained, what really exists is the presence of plug-flow and mixture which is known as a dispersed flow. In this case the equation of LEDov was used to determine the number of dispersion that although it is deducted from a model, it is not determined as a parameter of the same.

Table 2. Dispersion numbers obtained with the different models

General data				Traditional Models					Pérez [11]		
HRTt (min)	Q (ml/min)	V (L)	THR (min)	d SED	d SEDcov	d LEDcv	d LEDov	d TS	V (L)	d	THR
THR					Liquid phase						
308,9	1480	530	379	0.125	0.107	0.146	0.091	0.166	581	0.145	392
					In operation						
358,1	1489	460	326	0.071	0.065	0.077	0.058	0.083	499	0.080	335

THRt: theoretical hydraulic retention time, V: volume of the reactor, d:dispersion number, HRT: hydraulic retention time

According to the dispersion number, it could be observed that there is similarity between LEDov and the one proposed by [11]. However, the boundary conditions are not equivalent, and on the other hand [8] it does not propose a model for large extent of dispersion closed vessel (LEDcv), only an equation to determine the dispersion. The THR obtained with the equation 9 was similar to that obtained with the equation 13, but in this last the THR is a parameter of the model, which presented the best fitting to the experimental data and therefore it is more reliable, when the THR is obtained through dispersion there can be a mistake because the RDT curve is usually biased at the right side.

The Table 3 presents the pattern of flow of the BF. Negative dead spaces of 27.1% were found in the liquid phase, this is due to the presence of reverse flows that generate an effect of duplicity in the volume of the system.

Table 3. Pattern of the flow in the biological filter

THRt (min)	THR (min	β	I_p	I_d	I_m	%R
			Liquid phase			
308,9	392	1.271	0.916	-0.271	0.355	93.11
			In operation			
358.1	335	0.936	0.839	0.012	0.150	89.97

THRt= Time of theoretical hydraulic retention, β= hydraulic efficiency, I_p= fraction of plug volume, I_d= fraction of dead volume, I_m= fraction of mixed volume, %R=percentage of recovered tracer

The negative dead spaces are related to the hydraulic efficiency higher to the unit, which is possible and has happened in other investigations, [13]. An efficiency of 1.10 to THRt of 6 hours [16] and also values from 0.77 to 1.17 were found. Under operating conditions the BF showed small dead spaces (1.2%), indicating that its design provided an adequate use of its volume, which can be corroborated with hydraulic efficiencies close to the unity (1). For the BF in the two tested conditions, the piston flow predominated, it is important to highlight the fact that the flow behavior seen by the shape of the RDT explained before, coincides with the one obtained through the number of dispersion and the given flow pattern by [12].

Conclusions

In the two tested conditions in the BF; tap water and operation, the flow pattern showed tendency to piston flow, which coincides both with the analysis of the RDT as the flow pattern through the piston fractions, the mixture and the dead spaces. The dispersion in operating conditions was lower than when only tap water was used, which indicates that the marine shells used as support material increased the tendency to piston flow but decreased the mixture. The filter design with ascendent-descendent internal flow influenced the low dispersion found and therefore the theoretical piston flow tendency was achieved.

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