Revista EIA, ISSN 1794-1237 / Year XI / Volume 11 / Issue N.22 / July-December 2014 / pp. 59-67
Technical-scientific biannual publication / Escuela de Ingeniería de Antioquia —EIA—, Envigado (Colombia)

CHARACTERIZATION AND MODELING OF THE HYDRAULIC BEHAVIOR OF A UASB REACTOR

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ABSTRACT

The conversion rate of organic matter in a bioreactor depends on two main factors: the reactor's biological and hydraulic activity (Peña, Mara, & Avella, 2006). It is therefore necessary to understand treatment systems' hydraulic behavior by using tracer substances in order to determine flow behavior: piston, complete mix, dispersion; the existence of dead zones, short circuits, advective flows, and real hydraulic retention time. The goal of this article is to model the hydraulic behavior of a UASB (Upflow Anaerobic Sludge Blanket) system through a tracer test using rhodamine WT and the stimulus-response technique. The non-ideal flow models used were the tanks in series model and the dispersion model. We thereby determined that the UASB system being studied showed the behavior of a completely mixed reactor with short circuits and dead zones.

KEYWORDS: Hydraulic activity; UASB reactor; Flow behavior; Rhodamine WT; Tanks in Series Model; Dispersion Model.

CARACTERIZACIÓN Y MODELACIÓN DEL COMPORTAMIENTO HIDRÁULICO DE UN REACTOR UASB

RESUMEN

La tasa de conversión de la materia orgánica en un biorreactor depende principalmente de dos factores: la actividad biológica y la hidráulica del reactor (Peña, Mara y Avella, 2006). Por lo anterior, es necesario conocer el comportamiento hidráulico de los sistemas de tratamiento usando sustancias trazadoras a fin de determinar el comportamiento del flujo: pistón, mezcla completa, dispersión; existencia de zonas muertas, corto-circuitos, flujos advectivos y el tiempo de retención hidráulico real. El objetivo de este artículo es modelar el comportamiento hidráulico de un sistema UASB-*Upflow Anaerobic Sludge Blanket* (en español RAFA-Reactor anaerobio de flujo ascendente), por medio de una prueba de trazadores utilizando Rodamina WT a través de la técnica estímulo-respuesta, los modelos para flujo no ideal que se utilizaron son Modelo de Tanques en Serie y Modelo de Dispersión. Con ello se determinó que el sistema UASB en estudio tiene un comportamiento de un reactor completamente mezclado con presencia de cortocircuitos y zonas muertas.

PALABRAS CLAVES: actividad hidráulica; reactor UASB; comportamiento de flujo; rodamina WT; modelo de tanques en serie; modelo de dispersión.

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Paper history:
Paper received on:18-VI-2013 / Approved: 11-VII-2014
Available online: December 30 2014
Open discussion until December 2015

DOI: http:/dx.doi.org/10.14508/reia.2014.11.22.67-75

CARACTERIZAÇÃO E MODELAGEM DE DESEMPENHO HIDRÁULICO DO REATOR UASB

RESUMO

A taxa de conversão de matéria orgânica em um biorreator depende principalmente de dois fatores: atividade biológica e a hidraulica do reator (Peña, Mara, e Avella, 2006). Portanto, é necessário conhecer o comportamento hidráulico dos sistemas de tratamento que utilizam substâncias marcadoras para determinar o comportamento de fluxo: pistão, mistura completa, a dispersão; existência de curto-circuitos, zonas mortas, fluxos advectivos e o tempo real de retenção hidráulica. O objetivo deste artigo é modelar o comportamento hidráulico de um sistema UASB-Upflow Anaerobic Sludge Blanket, (UASB-reator anaeróbio de fluxo ascendente em portugues) por um teste traçador usando Rodamina WT através da técnica de estímulo-resposta, os modelos para fluxo não-ideal que foram utilizadas são do modelo de Tanque serie e Modelo Dispersão. Com isto se determinou que o sistema UASB em estudo tem um comportamento de um reactor completamente misturado na presença de curto-circuitos e zonas mortas.

PALAVRAS-CHAVE: atividade hidráulica; reator UASB; comportamento de fluxo; Rodamina WT; Modelo de Tanques em série; Modelo de Dispersão.

1. INTRODUCTION

The design of a water treatment system is based mainly on the biological processes that take place in the reactor. However, hydraulic events also appear, such as residence times, mixing times, flow regime, and reactor geometry. These can define the equipment's performance, setting parameters that can improve reactors' efficiency (Pérez & Torres, 2008), (Giacoman, Rejón, & Aguilar, 2006).

In waste water treatment reactors, we find the three states of matter: solid, liquid, and gas. The dynamic that can occur between these is directly related to treatment processes that can optimize the treatment system if it operates under proper hydrodynamic conditions.

Treatment systems show different matter transfer phenomena, such as diffusion, advection, filtration, sedimentation, etc., but these were developed empirically and are only currently being studied with a more rigorous theoretical basis (Giaçoman, 1998). However, there is still an information deficit, and better measurement techniques are necessary for a stronger theoretical foundation for these phenomena. One example is that mentioned by Rabiger (1988), in which the behavior of gas bubbles (for an aerobic system, air, and for an anaerobic system, methane) needs to be studied in a dynamic system in Newtonian and non-Newtonian fluids. Changes in local properties also need to be studied: density, viscosity, dispersion, speed, etc. for the fluid due to the effects of the movement of the other phases that appear, given that these changes can affect residence time (Giacoman, Rejón, & Aguilar, 2006).

The above supports the importance of hydrodynamic aspects that can develop in the different reactors that appear in waste water treatment systems. The goal of this article is to measure the residence times for an upflow anaerobic sludge blanket (UASB) reactor in order to obtain the reactor's distribution curves. We will also model the reactor based on non-ideal flow models, such as the tanks in series model and the dispersion model (Fogler, 2001).

2. METHODOLOGY

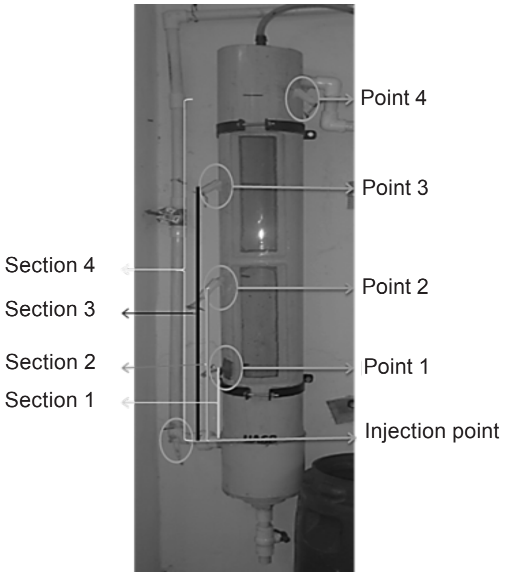
2.1. UASB reactor description

The study was carried out in the hydraulics laboratory at the Facultad de Minas (Mining Faculty) of the Universidad Nacional de Colombia in Medellín. The tributary enters in upflow from the feed tank, located at a height of 1.3m, by gravity and is distributed by a diffuser. The flow passes completely through the longitudinal profile and comes out the top toward the aerobic reactor. The reactor is made up of a primary sludge blanket zone which is at a height of 0.22m. The rest of the height is occupied by the phase separation zone containing the gas extractor, which moves the gas released in the fluidized bed away from it. The anaerobic system has 4 sampling points distributed along the longitudinal profile of the bed in order to observe the variance in hydraulic behavior along the reactor. **Table 1** presents the reactor's dimensions, and **Figure 1** shows the reactor's diagram.

Table 1. UASB reactor dimensions.

Dimensions	Measurements
Longitude (m)	1.44
Height (m)	1.22
Effective height (m)	1
Area (m^2)	0.02
Effective volume (L)	20
Total volume (L)	28.8
Theoretical flow rate (mL/min)	13.88
TRH (h)	24

Figure 1. Frontal view of UASB reactor



2.2. Experimental methodology

A tracer substance, rhodamine WT 20%, was used to evaluate the reactor's hydraulic behavior. This substance was chosen for its inert nature and was applied at the unit's entry point. The concentration of the substance was simultaneously measured at the reactor's outlet point and at the sampling points. This evaluation was made through experimental determination of the distribution functions of residence times using the stimulus-response technique. This technique consists of stimulating the system with a disturbance and observing the response to this stimulus at the reactor's outlet point. An analysis of the response will provide information about the behavior of fluid inside the system. In this study, the stimulus is an injection of tracer in the fluid that enters the unit, while the response is a representation of the tracer at different points in the reactor over time.

Before the tracer test was carried out, the flow was stabilized to a value close to the theoretical operation flow of 13.88 mL/min. The average flow was determined by adding together the flows obtained in each sampling period, giving an average flow of 14.18 mL/min.

2.3. Pulse injection

This study was based on suddenly and all at once injecting an input by pulse of 10ml of a rhodamine WT 20% solution with a concentration of 180000 ppb in the feed current that enters the reactor, as shown in **Figure 1**. The concentration was then periodically measured at the 4 sampling points during 51 hours. The tracer solution's concentration was determined considering that in section 1 of the reactor, there should have been a concentration between 0.4 and 400 ppb, which corresponds to the linear detection range for this piece of equipment: Aquafluor brand, model 8000-010.

2.4. Calculation methodology

With the information obtained, we proceeded to calculate and graph the distribution curves of flows and residence times. The curves C(t), E(t), F(t), and 1-F(t) were determined, as well as the dimensionless distribution function E(θ). These functions were later applied in order to analyze the type of flow in the reactor being studied using two models: dispersion and tanks in series. In order to analyze the tendency of the curves, we also calculated some parameters, t_i, t_p, t_m, t_c and t_{10} which, when related with the theoretical residence time t_0, give a detailed description of what occurred in each section of the reactor after injection of the tracer.

3. ANALYSIS AND RESULTS

3.1. Flow distribution and residence time curves

3.1.1. Curve C (t)

Curve of tracer concentration in the effluent over time.

Figure 2. Curve C(t)

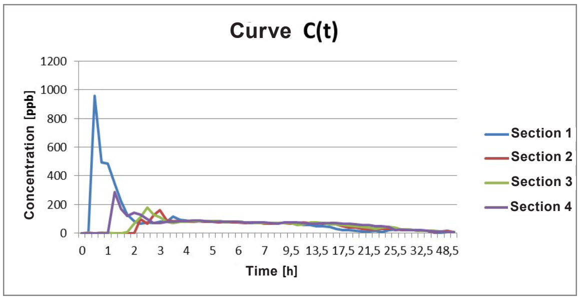
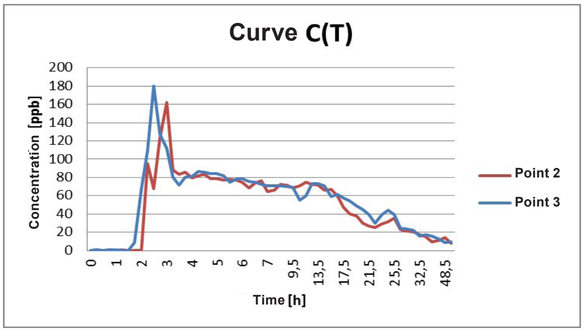


Figure 2 shows similar behavior in each section of the reactor. After the theoretical residence time of 24 hours, all of the tracer still has not come out with the effluent, which leads us to conclude that the real residence time is much longer than in theory.

The spikes that can be seen in each section of the analysis, that in section 1 being the fastest to register and that at section 2 being the last, lead us to conclude that the reactor has a stabilization time of approximately 4 hours. At later times, a falling tail appears in which the tracer concentration is similar for the four sections, allowing us to observe a homogenization after this point (Avella G, 2001).

In addition to the main spike in the first hours, the graphs of sampling points 2 and 3 also show a series of spikes after the stabilization period, which implies possible short circuits in the system. See **Figure 3**.

Figure 3. Curves C(t) , points 2 and 3



3.1.2. Curve E (t)

Physically, this curve shows the distribution of ages of the fluid that comes out of a recipient (Sánchez, 2010). This is due to the fact that the different elements in the fluid will take different amounts of time to pass through the reactor since they move along different paths. The distribution of these times in the fluid current that comes out of the reactor is called the age distribution of fluid at outlet (Levenspiel, 1981), (Fogler, 2001).

For constant flows E (t), this is determined using the following equation:

$$E\,(t) = \frac{C_i}{\sum C_i \Delta t_i} \qquad \textbf{(1)}$$

Considering the temperature gradients that modify the reactor's behavior, **Figures 4** and **5** show a growing behavior in the first two hours of the study for the four points. Here the system's hydrodynamic acclimatization could develop until achieving temporary equilibrium. The system later reached a normal condition of equilibrium toward a decreasing tendency of the system, similar to findings by Sánchez (2010).

Figure 4. Curve E(t), Point 1

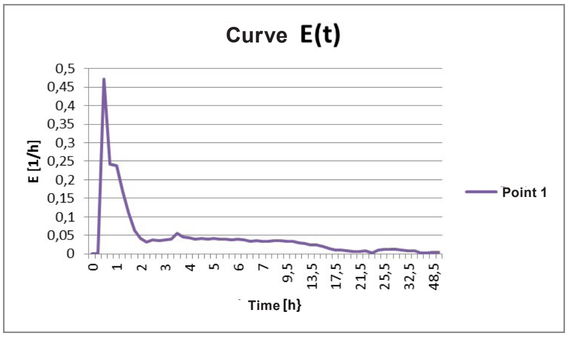
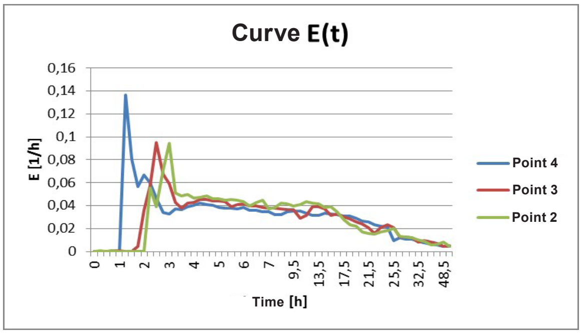


Figure 5. Curves E(t), Points 2, 3, and 4.



3.1.3. Curve F (t)

It is used to represent the accumulative concentration of the tracer at the outlet (measuring the concentration at the outlet in relation to its initial concentration [C/Co]); this function varied between 0 and 1 (Levenspiel, 1981).

For reactors with non-ideal flow and when the concentrations are given by a finite amount of data, the flow is constant, and the observation intervals Δt_i are equal, we have:

$$F(t) = \frac{\sum_{1=1}^{n} Ci}{\sum_{1=1}^{f} Ci} \qquad (2)$$

Figure 6. Curve F(t)

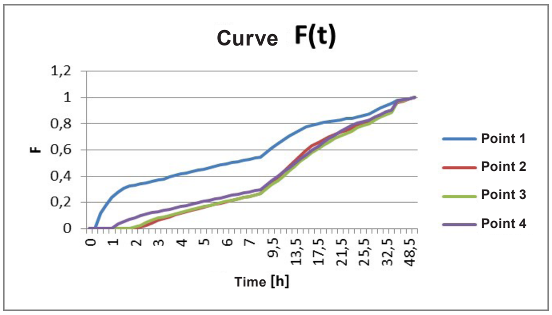
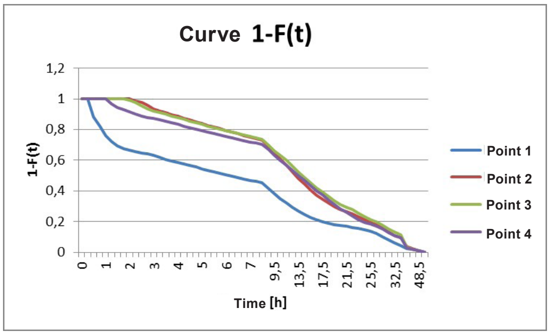


Figure 7. Curve 1-F(t)



From **Figures 6** and **7** we can determine that there is a different behavior between point 1 and the remaining points due to the fact that at point 1, the tracer moves more quickly through this section. During only the first 7 hours, approximately 55% of the tracer mass has passed through, while at the other points, approximately 30% of the tracer mass has passed.

3.2. Qualitative analysis of the concentration curves

The main parameters that must be considered when analyzing the tendency of the curve are registered in **Table 2** (Sánchez, 2010), (Arroyave Gómez, González Arteaga, & Gallego Suárez, 2004).

Table 2. Parameters

Parameter (h)	Point 1	Point 2	Point 3	Point 4
t_i	0,25	2,25	1,75	1,25
t_{10}	0,25	4	3,75	2,25
t_p	0,25	3	2,5	1,25
t_m	10,709	16,871	17,727	16,505
t_0	6	12	18	24
t_c	0,75	3,25	3,25	1,75
C_p, ppm	960,8	162,3	179,7	289,3

t_i: Initial time from when the tracer was applied to when it appears in the effluent.
t_p: Modal time, time until maximum concentration appears.
t_m: Median time, which corresponds to 50% of the tracer passing through.
t_0 : Theoretical retention time.
t_c : Time at which the concentration is greater than Cp/2.
t_{10} : Time at which the concentration is greater than Cp/10.
C_p: Maximum concentration at outlet point.

The following table shows the ratios between the experimental times and the theoretical time, with their respective interpretations.

Table 3. Ratios between experimental times and theoretical time

t_i / t_0	> 0,3	Indicates short circuits
	= 1	Piston flow
	= 0	Mixed flow
t_m / t_0	< 1	Indicates short circuits
	> 1	Indicates dead zones
t_p / t_0	≈ 0	Mixed flow dominates
	≈1 y $t_i/t_0 > 0.5$	Piston flow dominates
t_c / t_0	For a completely mixed reactor, this ratio is greater than or equal to 0.693	
t_{10} / t_0	For a piston flow reactor, it is close to the injection time, and for a mixed flow, it will be approximately 2.3	

Table 4 shows the respective results for each section.

Table 4. Results for time ratios

Ratio	Section 1	Section 2	Section 3	Section 4
t_i / t_0	0,042	0,333	0,208	0,094
t_m / t_0	1,785	1,406	0,985	0,688
t_p / t_0	0,042	0,250	0,139	0,052
t_c / t_0	0,125	0,271	0,181	0,073
t_{10} / t_0	0,042	0,333	0,208	0,094

Based on **Table 4**, we can consider that the reactor's hydraulics show the behavior of a completely mixed flow, as well as showing short circuits and dead zones.

3.3. Non-ideal flow models

With the parameters described above, it is possible to make a prediction about the hydraulic behavior of each section of the reactor using non-ideal flow models: a) dispersion model; and, b) tanks in series model.

To apply these models, we must normalize time θ_i.

$$\theta_i = \frac{t_i}{t_m} \tag{3}$$

in which t_m is defined as:

$$t_m \cong \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \tag{4}$$

3.3.1. Dispersion model

This model allows us to describe small deviations of the piston flow due to axial dispersion of the material, guided by Fick's Law, and transversal transportation resulting from molecular diffusion and convection. This model is described by the following equation (Fogler, 2001):

$$\frac{\partial C}{\partial t} = \left(\frac{D}{\mu L}\right) \frac{\partial^2 C}{\partial z^2} - \frac{\partial C}{\partial z} \tag{5}$$

In this model, it is considered that there are no dead zones or short circuits within the reactor. It corresponds to situations in which the flow does not deviate greatly from the piston flow. D/ μL, is a dimensionless parameter called the dispersion module and measures the degree of axial dispersion in the reactor (Levenspiel, 1981), (Fogler, 2001), (Cunill, Iborra, & Tejero, 2010).

$D/(\mu L) \longrightarrow 0$	Negligible dispersion, flows tends toward piston flow.
$D/(\mu L) \longrightarrow \infty$	Considerable dispersion, flow tends to complete mix.

In which:

D: is hydrodynamic dispersion, m^2/s.

L: reactor length, m.

μ: speed of flow in reactor, m/s.

An approximation for the dispersion module is made using normalized variance (Levenspiel, 1981).

$$\sigma_\theta^2 = \frac{\sigma^2}{t_m^2} = 2\frac{D}{\mu L} \tag{6}$$

The axial dispersion modules for sections 1, 2, 3, and 4 are 1.77, 0.70, 0.58, and 0.59, respectively. Since the dispersion modules found are small, the model can be described based on the following expression (Levenspiel, 1981). The dispersion modules were obtained by numerically solving **Equation 7**, used when there are large deviations from piston flow, $D/uL > 0.01$.

$$E(\theta) = \frac{1}{2\ \pi\theta\,(D/\mu L)} \exp\left(-\frac{(1-\theta)^2}{4\theta\,(D/\mu L)}\right) \tag{7}$$

Figures 8, **9**, **10**, and **11** show experimental curves E(θ) and curves E(θ) corresponding to the dispersion model for each section of the reaction.

Figure 8. Curve E(θ) for the dispersion model for section 1.

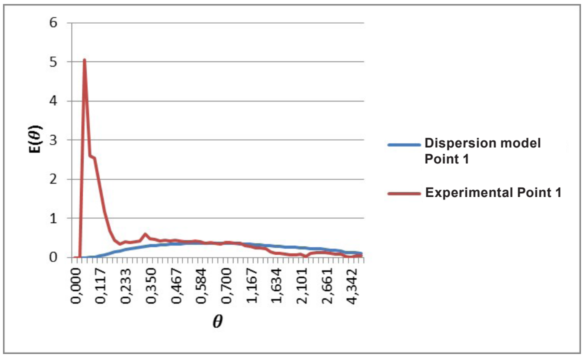


Figure 9. Curve E(θ) for the dispersion model for section 2.

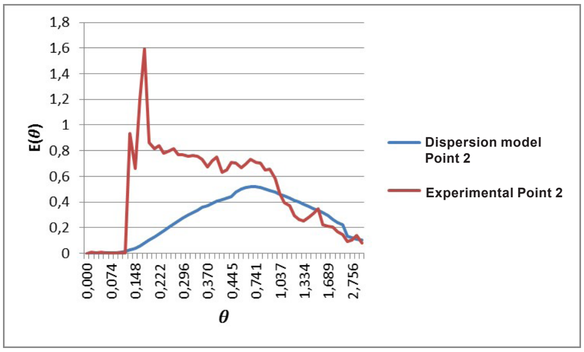


Figure 10. Curve E(θ) for the dispersion model for section

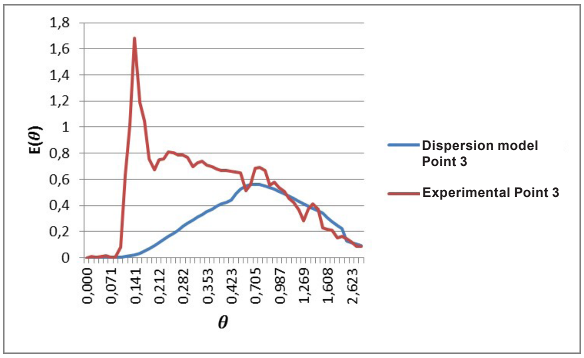
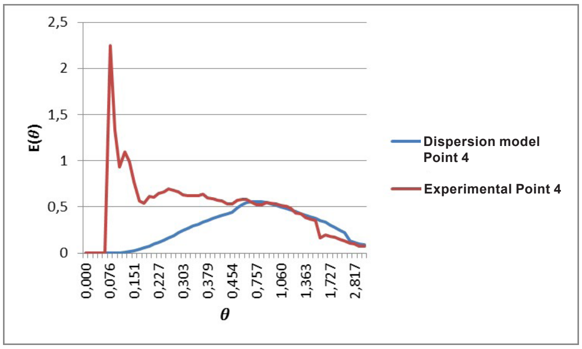


Figure 11. Curve E(θ) for the dispersion model for section 4.



Based on the graphs above, we can conclude that the reactor does not fit the dispersion model, as can be determined by the laminar flow regime that is present, or other hydrodynamic aspects not taken into account by the model, such as short circuits and dead zones, given that the model has only one parameter.

3.3.2. Tanks in series model

This model considers that the reactor can be represented by several equally-sized ideal complete mix tanks connected in a series. The only parameter is the number of tanks. Therefore, if the number of tanks is large, the flow will show piston flow behavior. On the other hand, is the number of tanks is small, the reactor's hydraulic behavior will tend to be that of a completely mixed flow.

The parameter of the number of tanks in series, N, is obtained based on normalized variance (Levenspiel, 1981).

$$\sigma^2_\theta = \frac{1}{N} \qquad (8)$$

Based on the ratio above, we found that the number of tanks for modeling the reactor in the different sections, 1, 2, 3, and 4, is 0.883, 0.349, 0.290, and 0.295, respectively. Since the model demands a whole number, we approach 1.

For the tanks in series model, curve E(θ) can be obtained using the following equation (Levenspiel, 1981):

:

$$E(\theta) = \frac{N(N\theta)^{N-1}}{(N-1)!} e^{-N\theta} \qquad (9)$$

Figures 12, **13**, **14**, and **15** show experimental curves $E(\theta)$ and curves $E(\theta)$ corresponding to the tanks in series model for each section of the reactor.

Figure 12. Curve *E*(*θ*) for tanks in series model for section 1

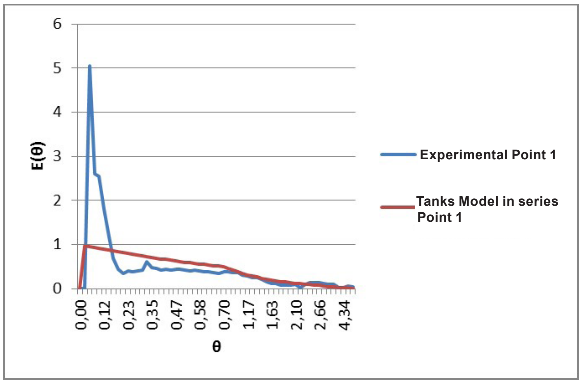


Figure 13. Curve $E(\theta)$ for tanks in series model for section 2.

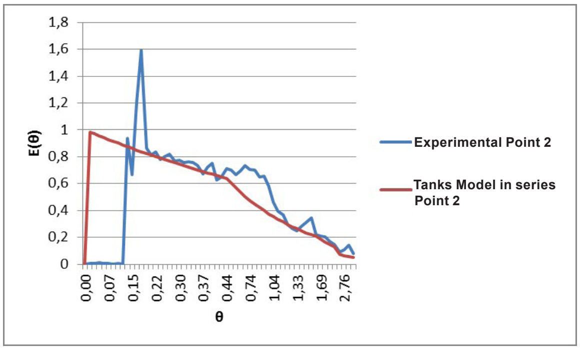


Figure 14. Curve $E(\theta)$ for tanks in series model for section 3.

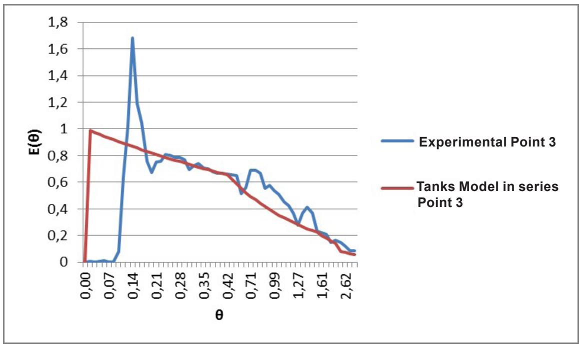
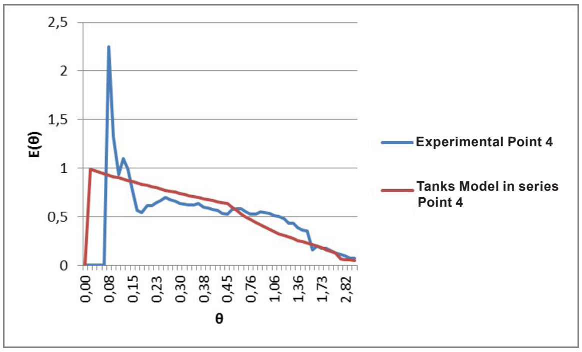


Figure 15. Curve $E(\theta)$ for tanks in series model for section 4.



In the curves above, we can observe that the tanks in series model coincides more precisely with the experimental curve than the dispersion model. The representation of curve $E(\theta)$ for the tanks in series model is more smooth due to the fact that it does not include the peak that appears in the experimental curve.

Since the number of reactors for all the sections in the reactor is between 0 and 1, we can conclude that there are short circuits and mixing (Cunill, Iborra, & Tejero, 2010).

4. CONCLUSIONS

The hydrodynamic characterization of the UASB reactor can be classified as a completely mixed reactor, but it shows short circuits and also dead zones. Even with the presence of short circuit zones and dead zones, the reactor's dynamic shows two characteristic periods: the stabilization period during the first 4 hours, approximately; and a pseudo-stationary period after these 4 hours when similar concentrations were obtained at the four sampling points.

The model that best coincided with the experimental curves was the tanks in series model for a number of reactors equal to 1. It did not, however, adequately model the first 4 hours corresponding to the system's stabilization period, given that the model shows a smooth curve during this period, while the reactor's real behavior showed pronounced spikes produced by short circuits such as those in the dead zones present in the reactor.

ACKNOWLEDGEMENTS

Our thanks to the hydraulics laboratory in the Facultad de Minas (Mining Faculty) of the Universidad Nacional de Colombia in Medellín. We also thank the engineer Luis Fernando Ospina. Finally, we are grateful to the company Gotta Ingeniería S.A.S. for their donation of rhodamine.

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Jojoa-Unigarro, G.D., Rodríguez-Zambrano, H.L. Cardona-Gallo. S. (2014). Characterization and Modeling of the Hydraulic Behavior of a UASB Reactor. Revista EIA, 11(22) July-December, pp. 59-67. [Online]. Available on: http:/dx.doi.org/10.14508/reia.2014.11.22.67-75