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DISPERSION MODEL TO DESCRIBE THE CARBON REMOVAL FROM WASTEWATER IN A FIXED BED UP FLOW PILOT BIOREACTOR WITH A HEXAGONAL FELDSPAR PACKING

MODELO DE DISPERSIÓN PARA DESCRIBIR LA REMOCIÓN DE CARBONO DE AGUAS RESIDUALES EN UN REACTOR DE FLUJO ASCENDENTE DE LECHO FIJO CON UN EMPAQUE HEXAGONAL DE FELDESPATO

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Abstract

In this work the modeling of carbon removal from wastewater in a fixed bed up flow pilot bioreactor with a hexagonal feldspar packing was carried out. The performance of a hexagonal feldspar packing was evaluated in an aerated biological pilot reactor. The feldspar packing was obtained by direct extrusion followed by sintering at 1100°C, during 4 hours, conditions at which the highest porosity and specific surface area were obtained. In addition to its easy preparation and low cost, the packing presented chemical resistance to different acids. The biological fixed bed up flow reactor with a total volume of 30.7 L was randomly packed with the hexagonal pieces of feldspar. Dispersion test were performed with a tracer (KCl), to estimate the dispersion number (*Nd*) in the reactor, with and without aeration. It was found that the dispersion increased due to the aeration and exerts a strong influence on reactor performance. A plug flow reactor model with axial dispersion and Monod kinetic was used to describe the carbon removal (COD) in the reactor at different hydraulic loading rates. The wastewater used during the tests was sampled at the exit of the primary settler of a Mexican wastewater treatment plant, being a mixture of industrial and urban effluents, with a COD = 650 mg/L. Four ascendant flow hydraulic loadings (L) from 1.08 x 10^{-4} ($m^3/s\ m^2$) to 4.32 x 10^{-4} ($m^3/s\ m^2$) were tested. The COD removal was about 95%, higher than the 85% reported in other studies.

Keywords: dispersion, modeling, feldspar packing, wastewater secondary treatment.

Resumen

En el presente trabajo se modeló la remoción de carbono de aguas residuales en un bioreactor piloto de lecho fijo de flujo ascendente con un empaque hexagonal de feldespato. El desempeño del empaque hexagonal de feldespato fue evaluado en el reactor piloto aireado. El empaque fue obtenido mediante extrusión seguida de un proceso de sinterizado a 1100°C durante 4 horas, en la cual se obtuvo la mayor porosidad y área superficial especifica. Además de su fácil preparación y bajo costo, el empaque de feldespato resultó ser resistente a diferentes ácidos. El reactor piloto, con volumen total de operación 30.7 L, fue empacado al azar con el soporte hexagonal de feldespato. Se realizaron pruebas con y sin aireación, para estimar el número de dispersión (*Nd*), utilizando como trazador KCl. Se encontró que la dispersión se incrementa con la aireación y ejerce una fuerte influencia en el desempeño del reactor. Para describir la remoción de carbono (DQO) se utilizo un modelo que considera la dispersión axial en el reactor, así como una reacción de remoción de tipo Monod que fue validado a diferentes cargas hidráulicas. Durante los experimentos se utilizó agua residual muestreada a la salida del sedimentador primario de una planta mexicana de tratamiento de aguas residuales. El agua residual es una mezcla de agua residual industrial y de agua residual domestica con una demanda química de oxigeno (DQO) de 650 mg/L. Las pruebas se realizaron con flujo ascendente y se probaron 4 cargas hidráulicas (L); desde 1.08 x 10^{-4} ($m^3/s\ m^2$) hasta 4.32 x 10^{-4} ($m^3/s\ m^2$). La remoción DQO alcanzó un 95 % lo cual es mayor a lo reportado (85%) en otros estudios.

Palabras clave: dispersión, modelo, lecho fijo, feldespato, empaque, reactor, flujo ascendente, agua residual.

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1. Introduction

The wastewater treatment by means of trickling filters has been applied to remove different pollutants (Peixoto, J, and Mota, 1998, Richard and Edgehill, 1999, Sá and Boaventura, 2001, Qun Hui *et al.* 2007). The wastewater is passed through a packed bed bioreactor where the biological film is attached. The microorganisms in the biological film remove the pollutants from the wastewater. Different packing materials as plastics, rocks, wood, glass, siliceous granular material, have been used in trickling filters (Sá and Boaventura, 2001, Peixoto, 1998, Eckenfelder, 1989, Ramalho, 1991). In comparison with activated sludge wastewater treatment, the trickling filters have different advantages e.g. high biomass concentrations are reached in the reactor, which reduces the treatment time. Additionally, the sludge separation from the treated wastewater is easier than in the case of the sludge activated systems. Depending on the packing material, the bioreactors depths are between 6 and 12 m and flow hydraulic loadings from 80 – 110 $m^2/d\ m^3$ are applied. (Tchobanoglous and Metcalf, 1991).

However, few have been done about the use of other low cost packing materials. Moreover, the models applied to describe the behavior of the process (Sá and Boaventura, 2001, Eckenfelder, 1989 and Raj and Murthy, 1999) have considered that the chemical oxygen demand (COD) removal follows a pseudo first order kinetics, as:

$$\frac{dS}{dz} = -kSX$$

where: k is the first order constant, S is the carbon measured as chemical oxygen demand (COD) and X the volatile suspended solids (VSS) concentration.

Moreover, the dispersion effect in the reactor has not been considered in the models, on the other hand, an ideal continuous stirred tank reactor (CSTR) or an ideal plug flow reactor (PFR) models have been applied (Edgehill, 1999 and Tekerlekopoulou *et al.*, 2008).

In this work the performance of a new and low cost hexagonal soda feldspar (Na_2O-Al_2O_3-$6SIO_2$) packing was evaluated in an aerated up flow biological film bed pilot reactor to treat a wastewater from a wastewater treatment plant. Moreover, a plug flow reactor model was applied in which the axial dispersion in the reactor and the Monod kinetic were considered to describe the removal of the chemical oxygen demand (COD) at different hydraulic loading rates.

2. Materials and methods

2.1 Reactor

The up flow biological film fixed bed reactor, 2.0 m height and 0.14 m internal diameter cylindrical Plexiglas column, with a total volume of 30.78 L was used.

The reactor has three sampling ports located at 0.5 m depth intervals (Fig. 1).

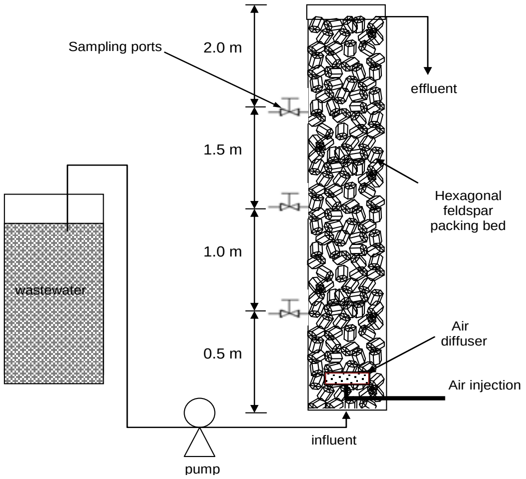

Fig. 1. Up flow biological reactor with a hexagonal feldspar packing bed.

The wastewater up flow rate was injected by means of a pump at the bottom of the reactor. An air flowrate of 0.3L/min was injected at the bottom in order to keep the dissolved oxygen (DO) concentration higher than 2.0 mg/L, which was measured with a DO electrode at the reactor exit, to ensure fast degradation of organics (Chuang, *et al.* 2007 and Tzu-Yi, 2004) and to keep oxygen from being rate limiting (Ritman and McCarty, 2001)

The experiments were performed with an actual wastewater sampled from the exit of the primary settler of a wastewater treatment Mexican plant. This wastewater results from the mixture of domestic and industrial wastewaters. The system was inoculated with activated sludge taken from the aerated reactor of the wastewater treatment facility. Then, the system was operated in batch during a start up period of a month to obtain an adequate thin biofilm, which covered the feldspar packing pieces. Afterwards, the operation was change to continuous mode and four ascendant flow hydraulic loading rates (L) were tested in the bioreactor; L1= 1.08×10^{-4} ($m^3/s\ m^2$), L2= 2.16×10^{-4} ($m^3/s\ m^2$), L3= 3.24×10^{-4} ($m^3/s\ m^2$) and L4= 4.32×10^{-4} ($m^3/s\ m^2$). After the each change of L, the reactor was operated during a week in order to reach the steady state. Then samples were taken out from each sampling port and at the exit of the reactor (effluent) at regular intervals, and the COD (APHA, 1995) in each sampled was measured.

2.2 Feldspar hexagonal packing

The bioreactor column was randomly packed with 120 hexagonal pieces of feldspar (Fig. 2a). The dimensions of the feldspar hexagonal pieces were 5.0

cm length, 6 concentric walls of 2.5 cm length. (Fig. 2b) The specific superficial area was 275.3 m^2/m^3 and each piece is about 52.0 g, in weight. The volume of the feldspar hexagonal packing was 5.78 L (23.2 %) and the liquid volume was 25 L.

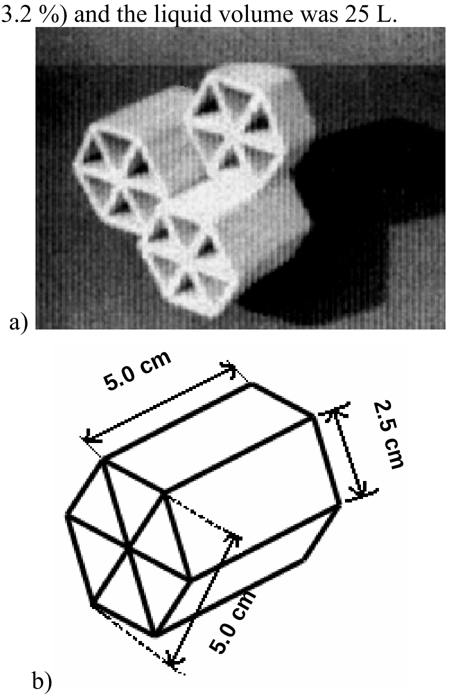

Fig. 2. a) Feldspar hexagonal packing, b) Dimensions of the hexagonal feldspar packing.

The feldspar hexagonal pieces were obtained by extrusion process followed of sintering at 1100°C (Rodríguez, 1999), and the effect of the sintering time on the material properties, as specific superficial area and porosity were evaluated. Porosity was measured using mercury intrusion, "Archimedes"-method (Bruckschen, *et al.* 2005). Structural longitudinal and cross-sectional stresses were performed on the hexagonal feldspar pieces in order to evaluate the weight it supports. Also, the chemical resistance was evaluated introducing the hexagonal feldspar pieces during 8 days, into 10% solutions of sulfuric, hydrochloric, nitric and hydrofluoric acids. In this case, the hexagonal feldspar packing weight was measured each 12 h and the weight lost was evaluated.

2.3. Dispersion tests

To evaluate the effect on the dispersion in the reactor, experiments were performed at two conditions; with aeration (air flowrate =0.3L/min,) and without aeration (air flowrate = 0.0 L/min). The experiments were performed in order to obtain the exit age distribution function (**E**) (Levenspiel, 1999). A pulse input of a no reactive tracer (KCl) was instantaneously introduced into the liquid entering (influent) into the reactor and the concentrations of the tracer in the liquid leaving the reactor (effluent) recorded by means of a conductivity meter. In these tests, tap water was used and the highest flow hydraulic loading of 4.32 x 10^{-4} ($m^3/s\ m^2$) was applied.

The dispersion number (*Nd = D / uL*), for the aerated and without aeration reactor was evaluated considering closed vessel as follows (Levenspiel, 1999):

$$\frac{\sigma^2}{\bar{t}^2} = 2\left\langle\frac{D}{uL}\right\rangle - 2\left\langle\frac{D}{uL}\right\rangle^2\left(1 - e^{-uL/D}\right)$$

2.4. Model

The model applied to describe the COD (*S*) removal in the liquid and volatile suspended solids (X) on the hexagonal feldspar packing in fixed bed reactor at the steady state, is shown in the eqs. (1) and (2). As seen, the dispersion effect, Monod kinetic and no biodegradable organic matter (*Sn*) are introduced in the Eq. (1)

$$\frac{D}{uL}\frac{d^2S}{dz^2} - \frac{dS}{dz} - \frac{(1-\varepsilon)}{\varepsilon}\frac{th\mu_{max}}{Y}\frac{(S-S_n)X}{Ks+(S-S_n)} = 0 \qquad (1)$$

The most largely used boundary conditions are (Dochain, 2001):

$$S - \frac{D}{uL}\frac{dS}{dz} - S_0 = 0 \text{ at } z = 0$$

$$\frac{dS}{dz} = 0 \text{ at } z = 1$$

The volatile suspended solids (VSS) concentration (*X*) as function of the reactor length (*z*) was estimated and is described by Eq. (2).

$$X = 18177e^{-0.907z} \qquad (2)$$

3. Results and discussion

Figs. 3 and 4 show the sintering time effect on the specific surface area and the material porosity.

As seen, in both cases the increase in sintering time produces a reduction in the specific surfaces area and the porosity.

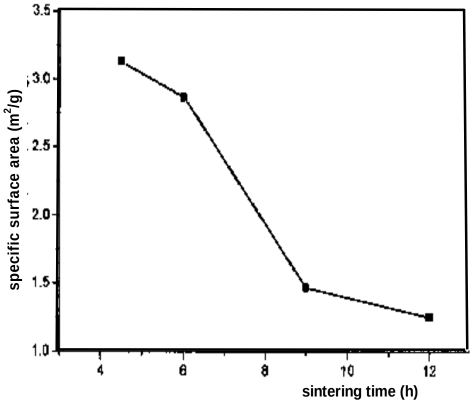

Fig. 3. Sintering time effect on the specific surface area.

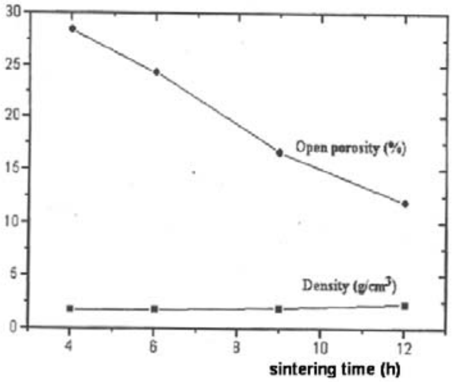

Fig. 4. Sintering time effect on the porosity.

Important features of the packing materials are the high surface area and high porosity which allows better and more biological film attachment to the media. Then, based on these results and the energy costs of the sintering process which is carried on at 1100°C, a sintering time of 4 hours was decided to applied in the production of the hexagonal feldspar packing. In addition, the structural longitudinal and cross-sectional stress was evaluated on the feldspar hexagonal pieces showed that the load it supports are 222.7 kgf y 54.8 kgf, respectively so it was estimated that hexagonal feldspar packing bed height can reach up to 6.0 m. The chemical resistance tests showed excellent chemical resistances to the 10% solutions of sulfuric, hydrochloric, nitric acids. However in the case of the hydrofluoric acid the weight lost reach the 100% after 100 h of contact time.

Fig. 5 shows the exit age distribution in the fixed bead reactor with and without aeration. As shown, in both cases there is a large dispersion in the reactor (> 0.01) (Levenspiel, 1999). This effect causes a non-ideal plug flow performance.

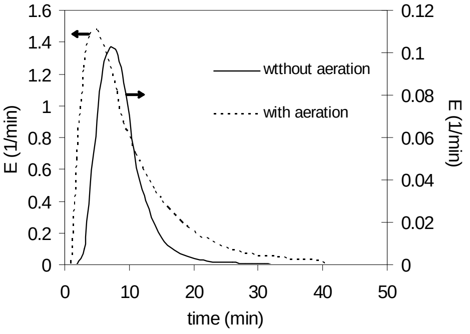

Fig. 5. Exit age distribution in the fixed bed reactor with and without aeration.

Based on these experiments, the dispersion number was evaluated. A = 0.099 was obtained for the reactor without aeration and a = 0.3927 in the aerated reactor.

In both cases the dispersion is large but the aeration increased the dispersion. As seen, the aeration produces a longer tail than in the case without aeration. It is important to remark the dispersion affects the reactor performance however, in other studies this effect had not been considered (Edgehill, 1999, Raj and Murthy, 1999).The dispersion number (*Nd*) = 0.3927 was used in the Eq. (1).

Fig. 6, shows the performance of the reactor at the four flow hydraulic loadings tested. The experimental results and the results obtained with the eqs. (1) and (2), and the boundary conditions are presented.

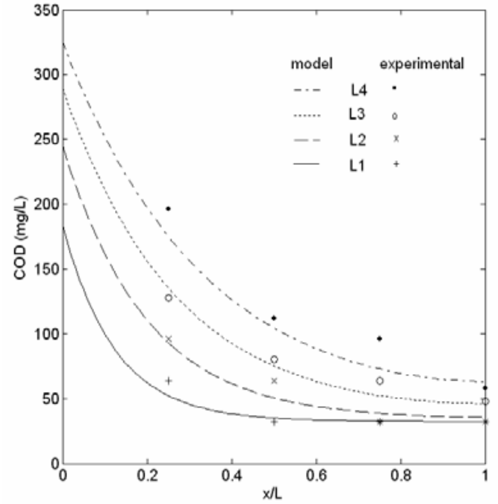

Fig. 6. Performance of the fixed bed bioreactor at the four wastewater flows hydraulic loadings (Model and experimental results).

As seen, the model fits well to the experimental dots, for the different hydraulic loadings. The figure shows that as the hydraulic loading rate increases the COD concentration at the reactor exit also increases, as reported by other researchers (Logan *et al.*, 1987, Raj and Murthy, 1999). Table 1 shows the COD removal at different hydraulic loading rates. At the lowest hydraulic loading rate (L1), the COD concentration = 32 mg/L in the effluent is achieved, value that corresponds to the non-biodegradable organic matter one, which is the lowest COD concentration that can be obtained during the biological process. Therefore, It will be necessary a tertiary treatment to eliminate the non biodegradable organic matter.

Table 1. COD removal at different hydraulic loading rates.

Hydraulic loading rates ($m^3/s\ m^2$)	COD effluent concentrations (mg/L)	COD Removal (%)
L1=1.08 x 10^{-4}	32.02	95.0
L2=2.16 x 10^{-4}	33.70	94.8
L3=3.24 x 10^{-4}	43.35	93.3
L4=4.32 x 10^{-4}	63.37	89.9

The COD removal is about 95% which is higher than the 85%, reported in other studies (Raj, 1999). In addition, the hydraulic loading rate of 1.08 x $10^{-4}$$m^3$/s m^2 (9.3 m^3/d m^2) used is almost twice than the hydraulic loading rate (5.0 m^3/d m^2) reported in those studies. As shown, in the same figure, the lowest COD concentration is reached at *z= x/L*= 0.5 or at a reactor height of the 1.0 m (at 2nd sampling port). After this point in the reactor there is no COD removal. For this reason at L1 the lowest COD concentration could be reached only with a 1.0 m height or 50% of the total volume of the bioreactor. Moreover, as L increases the COD concentration achieves higher and constants values at heights nearer the reactor exit. On the other hand, due to the dispersion, the COD of 650 mg/L of the influent drops immediately after the entrance to the bioreactor, to lower values depending on the hydraulic loadings. This is important to remark because in the case of the models applied in other works the concentration would fall slowly from the influent concentration, in this case from 650 mg/L. As shown in Fig. 7, the performance is affected by the aeration. If in the reactor there was no dispersion (= 0) the COD in the effluent would be 33 mg/L. Without aeration the dispersion is lower than with aeration and the concentration hypothetically would reach about 43 mg//L at the reactor exit (*z* = 1.0).

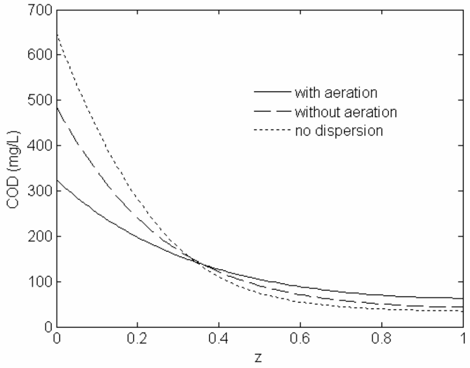

Fig. 7. Performance of the fixed bed bioreactor at different dispersion conditions (L4= 4.32 x 10^{-4} (m^3/s m^2).

On the other hand, at the actual conditions with aeration, the COD concentration of about 63.37 mg/L is reached at the reactor exit, then to reach a COD of 33 mg/L, it would be necessary to reduce the influent flow rate twice until reach a flow hydraulic loading about 2.16 x 10^{-4} m^3/s m^2. These results demonstrate that the dispersion in the reactor exerts a strong influence on the performance process, and then it is necessary to consider it in the modeling of the process. Finally, it is important to note that a Monod kinetic was used in comparison with the different works that consider a pseudo first order kinetic based on the situation that the process works at very lower COD concentration (*S«Ks*), however, it is no true because the concentration depends on the reactor height and is too high at the first part of the reactor.

Conclusions

The hexagonal feldspar packing shows a good performance during the biological wastewater treatment process and has excellent chemical resistance. In addition, it is easy to prepare and has low cost. During the experiments it was possible to remove about 95% of the influent COD. It is important to mention that it was demonstrated that the dispersion effect exerts a strong influence on the performance of the process, for this reason it is necessary to introduce this effect in the models. Moreover, the model used allows introducing other than pseudo first order kinetic (i.e. inhibition kinetic) which makes the model more consistent in comparison with the model used commonly.

Notation

D	dispersion coefficient, m^2/s
Ks	substrate saturation coefficient =322 mg/L
L	reactor length, m
S	reactor COD, mg/L
S_o	influent COD = 650 mg/L
S_n	non-biodegradable COD = 32 mg/L
$\overline{t}$	mean residence time
th	hydraulic residence time, h
u	flow velocity, m/s
x	reactor height, m
Y	heterotrophic yield (mg cell formed /mg COD oxidized) = 0.7
z	x/L

Greek symbols

ε	void fraction = 0.23
μ_{max}	specific growth rate = 0.04 h^{-1}
σ^2	variance

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