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EFFECTS OF BIOFILM GROWTH, GAS AND LIQUID VELOCITIES ON THE EXPANSION OF AN ANAEROBIC FLUIDIZED BED REACTOR (AFBR)

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Abstract—An anaerobic fluidized bed reactor, with 30 l sepiolite particles as support material was used to study the influence of biofilm growth and biogas production over hydrodynamic behaviour. It was verified that although gas production transforms the AFBR from a two-phase fluidized bed to a three-phase gas–liquid–solid system, the formation of a gas phase has little effect over hydrodynamic behaviour, and therefore it is possible to describe the bed as like a two-phase solid–liquid system. However biofilm development has a more important effect on the hydrodynamic behaviour, so it is necessary to reduce the recirculation ratio to maintain a set expansion, when the attached volatile solids increase. The superficial velocity necessary to maintain a 20% bed expansion, decreased from 11.5 m/h for clean particles, to 9.0 m/h for 20 g/l attached volatile solids concentration. The growth of the biofilm varies throughout the reactor, increasing the natural variation in the size of the particles in the bed.

Key words—biofilm growth, wastewater treatment, hydrodynamic behaviour, bed segregation, superficial biogas velocity, liquid velocity

NOMENCLATURE

b = parameter [equation (9)]
B_v = organic loading rate
d_p = particle diameter
d_s = support diameter
D = column diameter
g = gravitational acceleration
H = reactor height
k = parameter [equation (9)]
n = expansion index
Re_t = Reynolds number ($\rho \cdot d_p \cdot u_t / \mu$)
P = biofilm moisture
Q_g = biogas production
S = reactor section
SV_{att} = attached volatile solids conc.
t_R = hydraulic retention time
u = empty-bed liquid upflow velocity
u_g = superficial gas velocity
u_t = terminal particle settling velocity
$u_{t\infty}$ = terminal free-fall velocity
V = reactor volume
δ = biofilm thickness
ϵ = porosity
μ = water viscosity
ρ = water density
ρ_{bw} = wet biofilm density
ρ_c = crystalline density
ρ_s^{app} = apparent dry bed density
ρ_p = support density
ρ_w = wet bed density

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INTRODUCTION

The fluidized bed technology presents a series of advantages in anaerobic wastewater treatment, compared to other kinds of biological processes, that make it suitable. These advantages have been reported by different authors (Jewell, 1985; Hickey, 1990; Iza, 1991)

One of the most important variables in order to make correct decisions about the scale-up of the fluidized bed is its expansion, because this establishes the organic matter residence time in the biocatalyst zone, and is directly related with the process pumping cost.

The bacteria that carry out the anaerobic digestion of the wastewater contaminants, stick to the fluidized small particles, modifying their density, size and shape, and therefore their hydrodynamic behaviour. This implies that it is necessary to fit the recirculation ratio to the amount of attached microorganisms in order to maintain a fixed expansion of the bed.

Although the AFBR is a three-phase system, it can be studied like a classic solid–liquid fluidized bed, introducing the biogas effect as a correction of the predicted hydrodynamic behaviour (Fdz-Polanco and Diez, 1988). The solid–liquid fluidized bed has a regular expansion. The equation mostly used to describe the relation between the porosity and

the superficial velocity in a fluidized bed is the Richardson–Zaki equation (Richardson, 1971):

$$u/u_{t\infty} = \epsilon^n \quad (1)$$

where u is the empty-bed liquid upflow velocity, ϵ is the porosity of the bed, and $u_{t\infty}$ is the terminal free-fall velocity of the particles of diameter d_p placed in a column of diameter D. This velocity can be related with the terminal particle settling velocity, u_t, by correcting the wall effect:

$$u_{t\infty} = u_t \cdot 10^{-d_p/D}. \quad (2)$$

The exponent n, expansion index, by dimensional analysis is found to be a function of the Reynolds number, Re_t and the relationship between the diameters, d_p/D (Coulson and Richardson, 1981):

$$n = (4.4 + 18 \cdot d_p/D) \cdot Re_t^{-0.1} \; (1 < Re_t < 200). \quad (3)$$

These correlations originally developed for rigid solid particles can be applied for description of fluidization characteristics of bioparticles (Mulcahy and Shieh, 1987), although with the aim of performing a correct fluidized bed design and control program of the reactor, it is necessary to know terminal particle settling velocity (u_t) and Reynolds number (Re_t) as a function of bioparticles density, size and shape related with the extend of biofilm growth. The biofilm growth will affect not only hydrodymamics, but also volumetric removal rates. (Hermanowicz and Cheng, 1990).

According to Csikor *et al.* (1994), the terminal settling Reynolds number is not depending on biofilm thickness, because although terminal settling velocity changes sharply with changing biofilm thickness, this change is almost exactly counterbalanced by the change in particle diameter. By this reason fluidized bed expansion can be characterized in a simplest way by the superficial liquid velocity–porosity function.

MATERIALS AND METHODS

The experimental installation consisted of a plexiglass column 0.19 m internal diameter and 2 m tall, with six sampling ports numbered from below. The P1 sampling port is located 0.03 m up the feed inlet, and the other sampling ports are uniformly located with a separation of 0.33 m. The process flow sheet is shown in Fig. 1.

The reactor was continuously fed with synthetic wastewater prepared by mixing tap water and a concentrated solution of acetic acid, alkali and the required nutrients for microorganisms growth, mixed in the desired proportion by means of two pumps. The concentrated synthetic wastewater composition is presented in Table 1. Operational conditions of the AFBR, like the organic loading rate and the hydraulic residence time, were controlled by regulating the tap water and concentrated solution flows. In order to make data comparable, both organic loading rate and hydraulic residence time were based on the unexpanded media volume.

The reactor was filled with sepiolite up to 1 m height of fixed bed (30 l). Sepiolite is a fibrous clay, which has a porous and rough surface. This porosity and roughness of the carrier material surface protects the microorganisms from shear and has been used in previous studies (Huysman *et al.*, 1983; Maestrojuan and Fiestas, 1986; Iza *et al.*, 1987). The physical properties of the support material are not strictly uniform due to its natural origin. The average support material properties are presented in Table 2.

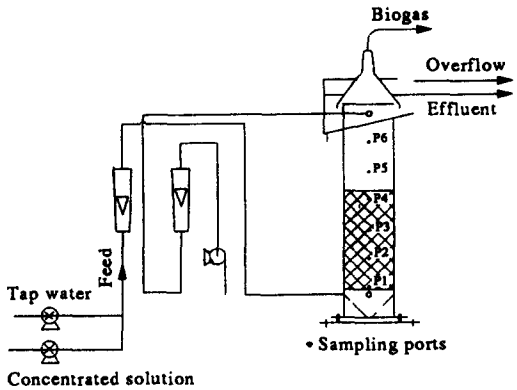

Fig. 1. Experimental installation.

Every week bioparticles were sampled at the different reactor levels, for determining the volatile attached solids concentration, the apparent density of the bed and the apparent density of the calcined bed. From these experimental values, the biofilm relative volume or relative thickness, its moisture, the wet biofilm density and dry biofilm density were calculated (Diez, 1991). Volatile attached solids concentration were determined by ignition losses of a sample of covered particles minus the ignition losses of the same volume of bare sepiolite. This procedure can lead to obtain negative values when the attached volatile solids is small.

EXPERIMENTAL CONDITIONS

The reactor was seeded with inoculum from a beet sugar factory UASB reactor. Operation temperature was 35°C.

In accordance with the hydraulic retention time, and organic loading rate used during the experimental work, it is possible to distinguish five periods of operation, characterized by the conditions shown in Table 3.

For each operational period, and fixed gas upflow velocities, it was possible to study the influence of liquid upflow velocity, by modifying the recirculation ratio, and the bed expansion. After each experiment, and with different biofilm accumulation, the relationship between liquid velocity and bed expansion without gas production could be investigated.

In this way, results comparing two consecutive experiments allowed the study of the influence of biogas production and biofilm growth on the hydrodynamic behaviour.

Table 1. Concentrated solution composition (g/l)

CH_3COOH	150
NH_4HCO_3	9.23
$NH_4H_2PO_4$	1.0
$MgSO_4.7H_2O$	0.6
$CaCl_2$	0.044
NaOH	40

Table 2. Average support material properties

Particle diameter, d_p	0.425–0.50 mm
Dry bed apparent density, ρ_B^{pp}	560 kg/m³
Particle density, ρ_p	1440 kg/m³
Crystalline density, ρ_c	2200 kg/m³

RESULTS AND DISCUSSION

Initial bed segregation

The carrier fluidization leads to particle segregation at the different fluidized bed height. The carrier material properties for each reactor level are presented in Table 4. Particle diameter was determined with a laser diffraction equipment Malvern Series 2600C.

In spite of the clear stratification of the bed, the experimental hydrodynamic behaviour of the clean particles fluidized bed can be described perfectly by means of the Richardson–Zaki equation proposed for uniform particles. For these particles the correlation determined was:

$$u = 144 \cdot \epsilon^{3.57} \text{ (m/h)} \quad (4)$$

Biofilm growth

Biofilm development was monitored by the growth of the attached volatile solids at the different levels. Figure 2 shows the temporal increase in attached volatile solids. The diagram shows the difference in the amount of growth on the particles located in the upper and lower parts of the reactor.

At the top the biofilm growth is faster and the attached volatile solids concentration increases with the organic loading rate, until organic over-load destabilized the process (on about 7 May 1990). This organic over-load led to the loss of biomass from the reactor, and was similar to the behaviour described by Veiga *et al.* (1992).

At the lower levels the microbial growth is slower, reaching only a half to a third of that at the surface. It remained practically constant when the organic loading rate was increased. As was indicated previously, in some cases the results are negative because of the experimental methods used to determine this parameter.

Biogas effect

Assuming that the biogas retained by the biofilm is negligible, and that the physical properties of the bioparticles are the same with and without gas production, the biogas effect on the hydrodynamic behaviour can be analyzed from consecutive fluidization experiences. Figure 3 shows the results obtained with four different gas upflow velocities. In each period a representation of liquid upflow velocity (u) vs porosity (ϵ) with gas production (filled squares) and without gas production (◆) is shown.

Table 3. Operational conditions of the AFBR

Period	B_v	t_R
	(g COD/L· d)	(h)
1	2	18
2	5	11
3	10	7
4	21	4
5	35	5

Table 4. Initial carrier material segregation in the fluidized bed

	ρ_w	ρ_B^{pp}	d_p
	(kg/m³)	(kg/m³)	(μm)
P5	1200	420	367
P4	1280	460	378
P3	1340	500	381
P2	1350	610	381

In these figures it is clear that in our operation conditions, the gaseous phase hardly modifies the two-phase fluidized bed expansion. Only a small decrease of the expansion of the three-phase bed was observed when the feed was suppressed and so biogas production dropped out quickly. This insignificant biogas effect on the hydrodynamic behaviour is in accordance with three-phase fluidized bed model proposed by Khang *et al.* (1983).

Equation (5) shows the relation between biogas upflow velocity and some design and operational variables. Biogas upflow velocity (u_g) can be calculated as biogas production (Q_g) divided by reactor section (S), but biogas production is proportional, for a constant removal yield, to organic loading rate (B_v) and reactor volume (V). Then, according to this equation and for a constant removal yield, the biogas upflow velocity is proportional to the reactor height:

$$u_g = \frac{Q_g}{S} \propto \frac{B_v \cdot V}{S} = B_v \cdot H \quad (5)$$

By means of the Khang model it is possible to predict that the compression of the bed, with regard to the two-phase fluidized expansion, for the higher experimental biogas upflow, is only of the order of 0.5%. By using the same model to predict the effect of a biogas when the upflow velocity is 6 times larger, i.e. representing a 6 m AFBR, then the biogas would produce only a 3% compression (Diez, 1991). That implies that biogas modification of the

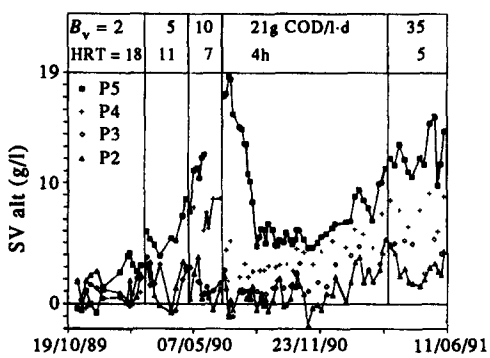

Fig. 2. Attached volatile solids concentration at different reactor levels.

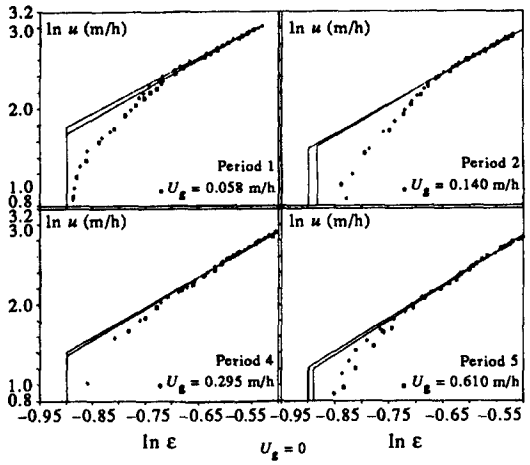

Fig. 3. Biogas effect on the fluidized bed expansion.

two-phase fluidized bed hydrodynamic behaviour is negligible.

In short the AFBR can be designed and operated, like a classic and better known two-phase fluidized bed and the effect of biogas can be ignored without introducing an important error.

Bed expansion

If the data in Fig. 3, together with other experimental results, are used to adjust the Richardson–Zaki equation then for porosities larger than 0.5, and expansions larger than 20%, the experimental results can be made to fit to the Richardson–Zaki correlation.

Below this expansion a gradual approximation to the fixed bed behaviour is observed. That means that for small liquid upflow velocities there are two regions: a fluidized upper region, and a static lower zone that increases when liquid upflow velocity decreases.

Figure 4 shows the results obtained from five fluidization experiments with different covered film thicknesses, together with the bed fluidization of the clean sepiolite particles.

Biofilm growth produces two effects on the fluidized bed hydrodynamic behaviour:

(1) The upflow liquid velocity necessary to maintain a set expansion decreases, due to the decrease of particle density and the decrease of the free-falling terminal velocity.

(2) Bed stratification increases, due to the non-uniform biofilm growth.

The effect of biofilm growth on the relationship between the upflow velocity and the expansion can be studied with regard to the attached volatile solids concentration.

Accepting that the particle shape is spherical, particle diameter and particle density can be related with the biofilm thickness, δ, and the wet biofilm density, ρ_{bw}, using the equations:

$$d_p = d_s + 2\cdot\delta \tag{6}$$

$$\rho_p = \rho_{bw} + (\rho_s - \rho_{bw})\cdot\left(\frac{d_s}{d_s + 2\cdot\delta}\right)^3 \tag{7}$$

where d_s is the support diameter, and ρ_s is its density.

On the other hand, biofilm thickness, δ, can be related with the attached volatile solids by the equation:

$$\delta = \frac{d_s}{2}\cdot\left[\frac{1}{\sqrt[3]{1 - \dfrac{SV_{att}}{\rho_{bw}\cdot(1-P)\cdot(1-\epsilon_{mf})}}} - 1\right] \tag{8}$$

where P is the biofilm moisture, and ϵ_{mf} is the bed porosity at the fluidization onset.

From the particle diameter and particle density it is possible to predict the free-falling terminal velocity through equation like:

$$u_t = \sqrt[2-k]{\frac{4\cdot g}{3\cdot b}\,\frac{(\rho_p - \rho)\cdot d_p^{1+k}}{\rho^{1-k}\cdot\mu^k}} \tag{9}$$

where the parameters b and k have been determined by several authors for different types of bioparticles, and different regimens of sedimentation (Table 5).

For our experimental conditions, and in previous experiences the values $\epsilon_{mf} = 0.41$ and $P = 0.94$ were determined. By replacing the values $b = 24$ and $k = 0.5$, obtained from data of the free-falling terminal velocity of the clean sepiolite in the equation (9), and then ignoring the contribution of bed stratification in the expansion determination, it is possible to predict the hydrodynamic behaviour for different attached volatile solids concentration, using the Richardson–Zaki's equation.

Figure 5 shows the hydrodynamic behaviour calculated for different covered bioparticle systems. Based on this figure can be predicted that the superficial liquid velocity necessary to maintain an expansion of 20%, decreases from 11.5 m/h for clean particles, to 9.0 m/h for 20 g/l attached volatile solids concentration.

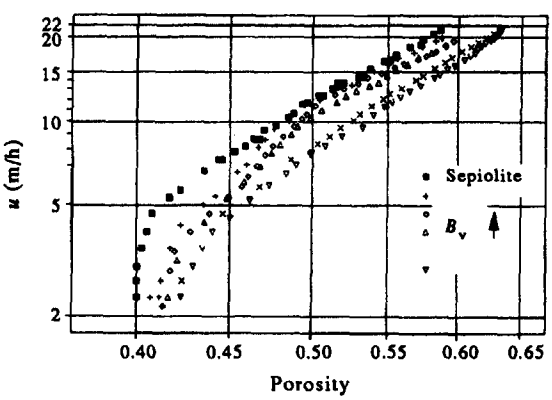

Fig. 4. Evolution of the bed expansion with the biofilm growth.

Table 5. b and k parameters for the terminal particle settling velocity determination

b	k	Re	Particle type	Reference
18.4	0.6	1.9–500	Rigid and smooth spheres	Perry (1963)
24	0.5	0.5–500	Rigid and smooth spheres	Levenspiel and Kunii (1969)
36.5	0.67	40–90	Biocovered	Mulcahy *et al.* (1981)
17.1	0.47		Biocovered	Hermanowicz and Ganczarczyk (1983)

Comparing this figure with the experimental results, Fig. 4, it can be seen that when the expansion is greater than 20% then the theoretical determination gives a good estimation of the AFBR behaviour with the attached volatile solids concentration. However, to have a better prediction of the AFBR expansion versus the SV_{att} when the expansion is less than 20%, and the bed is divided in a fluidized and a settled region, it will be necessary to introduce a term for bed stratification, due to the attached volatile solids variations at the different reactor levels.

CONCLUSIONS

In our experimental conditions the AFBR hydrodynamic behaviour was affected mainly by the biofilm growth, and the biogas production can be ignored. So our AFBR could be studied like a solid–liquid fluidized bed.

The two-phase bed expansion undergoes a small decrease due to the biogas production. Using the Khang *et al.* wake model, it was possible to predict that the biogas effect on the AFBR expansion will always be small.

Instead, the extent of biofilm growth on the bed expansion was found to be important, so it is necessary to reduce the recirculation ratio to maintain a set expansion, as the attached volatile solids increase.

The superficial velocity necessary to maintain a 20% bed expansion, decreases from 11.5 m/h for clean particles, to 9.0 m/h for 20 g/l attached volatile solids concentration.

Biofilm growth was also accompanied by an increase in bed segregation. At the upper reactor levels the attached volatile solids concentration were always greater than at the lower levels.

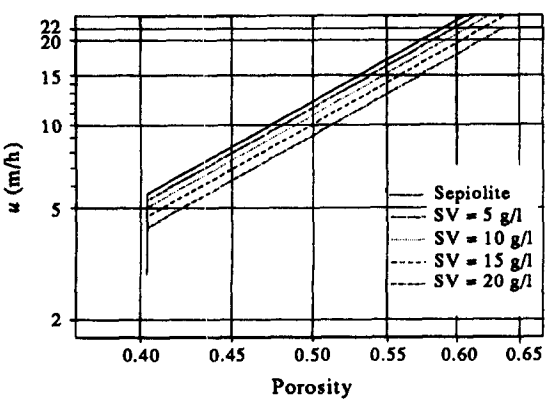

Fig. 5. Hydrodynamic behaviour prediction like a SV_{att} function.

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