Influence of pulsation on start-up of UASB reactors

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Abstract The aim of this work is to study the influence of pulsation on the start-up of lab-scale UASB reactors. Pulsation was produced by an Elastic Membrane Pulsator (EMP). The application of this device in previous works improved the performance of continuous fixed-bed fermentors and reduced the formation of preferential pathways, the retention of gas metabolites within the bed and the resistance to mass transfer. These characteristics seem to be suitable for feeding UASB reactors. In this work, the influence of pulsation frequency was studied in two pulsed UASB reactors operated in parallel with a non-pulsed one. One of them (P1) operated at high frequencies (periods of 50 and 200 s between each pulsation) and the other (P2) at low frequencies (periods of 3600 and 900 s between each pulsation). An important improvement of the removal efficiency for pulsed reactors with respect to the non-pulsed one was obtained. The structure of the biomass was observed at the end of the process by scanning electron microscopy. In general, granulation of biomass was improved when operating in pulsing form.

Keywords Granulation; mass transfer; process efficiency; pulsation; start-up; UASB

Introduction

Anaerobic technology has been proved to be useful for the treatment of concentrated wastewater. However, one of its main disadvantages is the long start-up period required for the development and retention of high concentrations of active and well balanced biomass inside the reactor (Rintala, 1991). This is usually achieved by a progressive increase of the Organic Loading Rate (OLR) up to the design value. OLR values must initially be low, of the order of 1 kg COD/m³·d, causing poor hydraulic mixing, especially in UASB reactors, and impeding a proper mass transfer between the three phases present in the reactor. In fact, it may take 4–8 months before a steady state is reached in this kind of process.

The application of external energy in pulsing form has been a common practice to improve mass transfer rate in chemical engineering units, including biochemical reactors. In this last case, it also avoids gas retention between the bioparticles, which reduces the effective reactor volume and impedes an efficient contact between the dissolved organic matter and cells (Sanromán et al., 1994). In some cases, pulsation also allows the stability of the pH inside bioreactors to be increased, mainly due to an improvement in the distribution of substrate and to the slow movements of the bed (Etzold and Stadlbauer, 1990). The purpose of a particular pulsing device depends on the type of problem to be solved. In some cases, the interest is focussed on increasing the mixing inside the system, while in other cases the objective is to maintain plug flow hydraulics (Roca et al., 1996).

The main objective of this work is to study the influence of pulsation on the start-up and operation of lab-scale UASB reactors. The effect of pulsation frequency was studied using two UASB reactors operated in parallel. One of the reactors was operated at high frequencies and the other at low frequencies.

Materials and methods

The experiments were carried out in three identical lab-scale UASB reactors of 0.8 l of...
overall volume operated at 37°C. Two reactors were equipped with an elastic membrane pulsator (Roca et al., 1994; Lema et al., 1995) and the other one was operated without pulsation (NP) as a blank. In this case, the elastic membrane pulsator (EMP) consists of one elastic tube connected to an electrovalve which is opened and closed by a timer or a computerised system. The pulsation frequency is given as $f = 1/(t_s + t_o)$ where $t_s$ and $t_o$ are the electrovalve shutting and opening times, respectively. A fixed $t_o = 1$ s was used during the experiments. In the first reactor (P1), both recycling and feeding flow were pulsed by the EMP, while in the second one (P2), only the feeding was pulsed. Due to the continuous recycling flow in P1, pulsation could only be set at high frequencies and small amplitudes. In P2, it was necessary to operate at low frequencies and high amplitudes to accumulate sufficient volume inside the EMP and achieve the desired pulsing effect. The three reactors were inoculated with 330 ml of flocculent sludge from an UASB reactor treating fish-cannery wastewater, with a concentration of 27 g VSS/l, a specific methanogenic activity of 0.27 kg COD/kg VSS·d, and a sludge volumetric index (SVI) of 18.3 ml/g TSS.

A synthetic tap water solution of monohydrated dextrose was fed to the reactors as the carbon and energy source with a concentration equivalent of 5 g COD/l in the first part of the experiment, while in the second part, the concentration of dextrose was doubled in order to obtain 10 g COD/l. NH₄Cl and K₂HPO₄ were used as nitrogen (N) and phosphate (P) sources, respectively, to ensure a COD:N and COD:P ratio of 1:0.018 and 1:0.0028, respectively. Both values are compatible with normal bacterial needs. To supply sufficient pH-buffering capacity to the system, 1 g Na₂CO₃/g COD was dosed.

The parameters measured were Chemical Oxygen Demand (COD), Volatile Fatty Acids (VFA), alkalinity, Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS), Specific Methanogenic Activity (SMA) and biogas composition. COD was determined by a semi-micro method (Soto et al., 1989). VFA was determined by Gas Chromatography Hewlett-Packard 5890A, equipped with a Flame Ionisation Detector (FID) and alkalinity was measured by titration with sulphuric acid (Ripley et al., 1986). The SMA was determined according to the method described by Soto et al. (1993). The structure of the biomass was observed by scanning electron microscopy (SEM) using a Digital SEM LEO 435 VP controlled by computer, with achievable magnifications between 15× and 290,000×.

Results and discussion

Two start-up experiments were performed to test the bioreactor performance with the proposed pulsing device. The shutting times ($t_s$), the frequencies and the ratios of pulsed volume ($V_p$) over the reactor volume ($V_r$) applied to reactors P1 and P2 during experiments 1 and 2 are indicated in Table 1. For reactor P1, the pulsed volume was kept constant decreasing the recycled flow rate as the feeding flow rate increased, while for reactor P2 this volume increased proportionally to the OLR. Shutting time, $t_s$, was reduced on day 21, by 50% in both experiments (1800 and 900 s, respectively), in order to decrease the volume of each pulsation.

In experiment 2, the frequency decreased for reactor P1 and increased for reactor P2 with respect to experiment 1. The logic of determining experiment 2 in this way comes from the results obtained from experiment 1. For reactor P1, these results were good in the

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<th>Table 1 Shutting times ($t_s$), frequencies ($f$) and pulsed volume ($V_p$)/reactor volume ($V_r$) ratio</th>
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<td>$t_s$ (s)</td>
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<tr>
<td>Experiment 1</td>
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<td>Experiment 2</td>
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first experiment. However, it was desirable to decrease a little the frequency, since the feeding equipment presents less operating drawbacks at lower frequencies. On the contrary, in reactor P2 the frequency was increased since not very good results were attained with the lower frequencies employed in the first experiment.

**Removal efficiency**

The Organic Loading Rate (OLR) applied to the reactors in both experiments was simultaneously and progressively increased from 1 to 10 kg COD/m³·d operating with an influent concentration of 5 g COD/l (Figures 1a and 1b). On day 38, the OLR was suddenly increased to 20 kg COD/m³·d by changing the COD concentration up to 10 g/l while the added alkalinity was reduced by 50%.

COD removal in the three reactors is presented in Figures 2a and 2b vs the applied load. The values reported in these figures are average values referring to 10 day intervals. During experiment 1, the highest COD removal (94%) was observed for P1. The performance of reactor P2 was very similar at the beginning of the experiment, while the efficiency, i.e. the percentage of COD removed with respect to the COD of the influent, decreased to 85% when working at an OLR of 12.5 kg COD/m³·d. This fact could be due to the reduction of $t_p$ from 3,600 to 1,800 s and consequently the pulsed volume (pulsation amplitude). Low amplitude pulsation causes a minor mechanical effect and thus a poor mass transfer (Roca et al., 1996). For the non-pulsed (NP) reactor, COD removal was 85% on average at high OLR values, which is remarkable lower when compared to the values obtained in P1.

In the second experiment (see Figure 2b), COD removal was about 95% during the whole operation for both reactors P1 and P2, even at the highest OLR values. The removal efficiency of the NP reactor was always below 90%, decreasing to 50% during the last part of the experiment. The great decrease in the removal capacity observed during NP reactor operation in this last experiment can be explained by the continuous wash-out of biomass from the reactor as the OLR and the biogas production increased. This could be induced by

![Figure 1](https://iwaponline.com/wst/article-pdf/45/10/163/424760/163.pdf)  
**Figure 1** OLR applied to pulsed (P1 and P2) and non-pulsed (NP) reactors in experiments 1 (a) and 2 (b) P1 —, P2 —, NP L

![Figure 2](https://iwaponline.com/wst/article-pdf/45/10/163/424760/163.pdf)  
**Figure 2** COD removal in pulsed (P1 and P2) and non-pulsed (NP) reactors in experiment 1 (a) and 2 (b) P1 —, P2 —, NP L
a deficient degassing of the bed when fed without pulsation. However, the percentage of COD removal in P2 improved with respect to the first experiment and the values measured for P1 were very similar. The better behaviour of reactor P2 in this last experiment could be explained by the higher frequencies employed, this resulting in a similar hydraulic behaviour with reactor P1.

Alkalinity

Intermediate Alkalinity (IA) and Total Alkalinity (TA) are shown in Figures 3a and 3b. The values obtained from the pulsed reactors in the two experiments were at all times below 0.3, which is the limit recommended for maintaining reactor stability. Only in the last part of the operation, P2 presented a value slightly higher than this limit, due to the presence of VFA in the effluent. However, the increase in the alkalinity ratio for NP is noticeable in the last part of the two experiments (from day 31), especially in the second one, where this value increased progressively to 0.7. This fact indicates a serious destabilisation that is confirmed for the high concentrations of acetate and propionate measured in the effluent (0.822 and 0.470 g/l, respectively).

The evolution of TA (Figure 4) was very similar for the three reactors during the two experiments, except for the last part of the operation. In experiment 1, the change of feed (day 38) provoked a diminution in TA in the three reactors, as expected, this effect being more significant in P1 and NP. However, the performance of pulsed reactors in the second experiment was not affected by low alkalinity. The contrary was observed in the NP reactor, with a decrease at almost 50% in TA from day 38.

Specific methanogenic activity

Specific Methanogenic Activity (SMA) tests for the sludge of the three bioreactors were carried out at the middle and at the end of both experiments. The average results are shown in Table 2.
It can be seen that the SMA values for the pulsed reactors are slightly higher than in the NP reactor in the two experiments, reflecting the better methanogenesis of biomass, as expected from the operation of P1 and P2.

### Biogas composition

Biogas composition was monitored from day 23. Figures 5a and 5b show the evolution of the CO₂/CH₄ ratio at different values of the OLR.

The CO₂/CH₄ ratio for P1 and P2 in experiment 1, varies between 0.5 and 1, reaching this last value when working at high OLR, whereas during the second experiment it had an almost constant value (0.5). This ratio is an additional indicator of the better performance of the pulsed reactors with respect to the NP reactor, since a better conversion to methane is produced in the pulsed ones.

### Biomass characterization

In the last day of the experiments, sludges were sampled from the three reactors and a microscopic characterization was carried out by means of scanning electron microscopy. A structure with bacteria well immobilised in pellets throughout the sludge bed was found in reactors P1 and NP, while P2 only presented granular structure in the bottom part, with flocculent sludge in the upper part. As shown in Figure 6, pellets formed in the pulsed reactors presented a well defined round structure with evidence of channels on the whole surface, while the pellets formed in the NP reactor showed a compact outer layer almost without channels. The presence of those cavities and holes facilitates biogas release and may facilitate the entrance of nutrients to the inner core of the granule. In the second experiment, the presence of granules was observed in the bottom part of reactors P1 and P2, with the typical flocculent structure and granules in formation (Figure 7). No agglomeration of biomass was observed in the sludge sampled from the NP reactor.

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<tr>
<th>SMA (g COD/g VSS d)</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
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<tr>
<td>P1</td>
<td>0.46 ± 0.04</td>
<td>0.56 ± 0.015</td>
</tr>
<tr>
<td>P2</td>
<td>0.45 ± 0.025</td>
<td>0.54 ± 0.055</td>
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<tr>
<td>NP</td>
<td>0.39 ± 0.01</td>
<td>0.46</td>
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**Table 2** Specific Methanogenic Activity (g COD/g VSS d) of the sludge from reactors P1, P2 and NP

**Figure 5** CO₂/CH₄ ratio of biogas from pulsed (P1 and P2) and non-pulsed (NP) reactors in experiment 1 (a) and 2 (b) —, P1 —, P2 L NP
Conclusions

Three laboratory-scale UASB reactors were fed at similar loading rates at the same operational conditions, the only difference being pulsing of the inflow. A maximum 95% COD removal was attained for the pulsed reactors, whereas in the non-pulsed reactor, removal efficiency decreases to 80%. It is assumed that pulsation favours a better degassing of the sludge bed when biogas production is high, and this avoids severe loss or even wash-out of the sludge, as occurred in the NP reactor during experiment 2.

Pulsation promotes hydrodynamic stress in UASB reactors, which facilitates the agglomeration of flocculent biomass into granules. It also improves the liberation of gaseous metabolites trapped within the bed, avoids the formation of preferential channels and improves mass transfer. All these effects lead to an increase in removal efficiency in pulsed reactors when compared to non-pulsed ones. It can be concluded that influent pulsation is a possible way of improving the hydrodynamics and the treatment process efficiency of UASB reactors.

References


