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THE EFFECT OF THE LIQUID UPFLOW VELOCITY AND THE SUBSTRATE CONCENTRATION ON THE START-UP AND STEADY-STATE PERIODS OF LAB-SCALE UASB REACTORS

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ABSTRACT

This research was carried out in order to study the effect of the upflow liquid velocity (ULV), the COD concentration, the volumetric loading rate (VLR) and the hydraulic loading rate (HLR) on the start-up and steady-state performance of UASB reactors treating soluble substrate with 3,000 mgCOD/l at mesophyllic temperature (35^{o}C).

Three lab-reactors (UASB) were constructed with different liquid volumes, and also with different cross-sectional areas. The three UASB reactors were started up with the same biological loading rate (BLR), but the start-up procedures were based on different criteria.

After the start-up had been carried out successfully with the formation of the granules, all the three UASB reactors were operated under steady-state conditions for up to eight different HRT(s), namely: 16, 14, 12, 10, 8, 6, 4 and 2 hours.

For each of the three reactors the kinetic parameters were determined using the Monod model. Analysis of the influence of the operational factors and reactor design on the kinetic coefficients is described. The results indicate that the liquid upflow velocity has considerable effect on the sludge in this type of system, thereby acting as a selective process in the cultivation of the biomass.

Analysis of sensitivity on the kinetic parameters indicated which was the most sensitive kinetic parameter for these reactors.

KEYWORDS

Upflow anaerobic sludge blanket (UASB) reactor; start-up; steady-state; granulation; specific methanogenic activity (SMA); upflow liquid velocity (ULV); biological loading rate (BLR); volumetric loading rate (VLR), hydraulic loading rate (HLR).

INTRODUCTION

In recent years numerous designs have been developed to optimize the anaerobic treatment of wastewater. The Upflow Anaerobic Sludge Blanket (UASB) System is one of them, and since this system is well known, just the main outlines will be stressed here.

The UASB reactor can be briefly described as a system with specific characteristics in terms of design, start-up and performance. Physically, the system is quite simple and consists of an inlet for substrate distribution, a chamber in which all reactions occur and which can either have a mixer or not, and at the top a three-phase-separator (TPS), which separates the solid particles from the liquid and gas, allowing the last two to leave the system. The substrate in this system passes first through a bed of sludge (containing a high concentration biomass) that may be granulated or flocculent, then it passes through a less dense biomass, called the blanket, and at the top of the reactor, before the effluent is discharged, the TPS separates the liquid, solid and gas fractions. The major advantage of the UASB process in which no specific support material is required, may also be one of its main drawbacks. Thus, the system must develop a sludge that can be retained in the reactor with good settling characteristics and with a SVI of less than 40 ml/g for flocculent sludge and less than 20 ml/g for granular sludge. The ideal sludge developed in this type of reactor is referred to as granular sludge (Hulshoff Pol et al., 1984). This occurs when the flocculated and dispersed biomass begins to aggregate and grow in the form of spherical flocs with good structural properties, resistant to hydraulic forces and with exceptional physical and biological aspects. Since granulation has been discovered accidentally (de Zeeuw, 1987), this type of agglomeration of anaerobic microbial populations has been proven to be a powerful tool in the development of a new wastewater technology. Considerable research has been carried out into some of the physical, biological and chemical factors responsible for this phenomenon; however, information on this matter is still relatively inconsistent (Hulshoff Pol et al., 1987), and therefore more research about this process is still in great need.

OBJECTIVES

Up to now, one of the main problems encountered has been to obtain granules in a UASB reactor with an unacclimatized inoculum in the shortest period possible. Therefore, it was considered desirable to test different configurations of this type of system, in order to investigate the influence of upflow liquid velocity (ULV) on the process of sludge cultivation which leads to granulation. Furthermore, it was thought to be important to determine the kinetic parameters e.g. microbial growth and substrate utilization of the granulated biomass, not only because of the lack of information concerning this particular field, but also to investigate the influence of the hydraulic parameters imposed on the microbial populations involved in the process.

MATERIAL AND METHODS

This section describes the materials and methods which are common to many of the experimental researches. The major parameters and analytical methods employed in this research are listed in Table 1. A brief description of the non-standardized analysis employed is given below, since a more detailed description can be found elsewhere (Campos, 1990).

TABLE 1 Analytical Methods Employed

Parameters	Analytical Methods
Total Solids* (TS)	Standard Methods (1985)
Volatile Solids* (VS)	" " "
Suspended Solids (SS)	" " "
Total Phosphorus	" " "
Ammonia Nitrogen	" " "
Organic Nitrogen	" " "
Chemical Oxygen Demand (COD)	" " "
Volatile Fatty Acids (VFA)	Chromatography
Gas Composition	"
Alcohol	"
Total & Inorganic Carbon (TC&IC)	TOC Analyzer
Metals	Atomic Absorption
Hydrogen*	Hydrogen Analyzer
SMA-test*	Conventional and Warburg

* These analyses will be explained further.

Laboratory reactors

The three lab-reactors were constructed from plexiglass cylinders, glass funnels and rigid PVC. Each had different designs in terms of body length, diameter and three phase separator (TPS), see Figure 1. The total volume of the reactors were 7.9, 3.1 and 16.6 litres for reactors 1, 2 and 3 respectively.

Specific Methanogenic Activity Test (SMA-test)

The SMA-test was carried out using two different methods.

First: to start-up the reactors a conventional SMA-test was employed to test the seed sludge, using a set of five one-litre batch reactors with magnetic stirrers. The biogas volume was measured using water displacement in a graduated glass tube (Campos, 1990). The problem of this test is related to its accuracy, since the pressure cannot be kept constant. The problem can be minimized when the amount of sludge available to be tested is quite large.

Secondly: a new methodology for the SMA-test was developed during the experiment, in order to allow the measurement for the small quantity of sludge available for the test. For this purpose an adapted Warburg respirometer was successfully employed (James et al.,1990 ; Campos, 1990 ; Anderson et al., 1991 ; Campos and Chernicharo, 1991 and Chernicharo and Campos, 1990).

Solids

The sludge withdrawn for measuring the concentration of solids inside the reactor was collected throughout the profile using the sampling ports, from the top to the bottom in order to minimize mixing between ports. The solid concentration analysis was performed bypassing the first step (steam bath). This procedure was mainly carried out due to the number of samples which should be analyzed simultaneously. For this purpose special trays were used, each one capable of holding eight 10 ml porcelain dishes (crucibles). The drier time in the oven at 104°C was extended for three hours due to the volume of sludge. The sampling procedure was planned carefully because anaerobic sludge tends to deteriorate immediately after collection. Analysis such as SS, VS, TC, IC, COD and organic acids were determined directly after collection, while others, which did not deteriorate with storage, eg. metals, were kept at 4°C until analysis was possible.

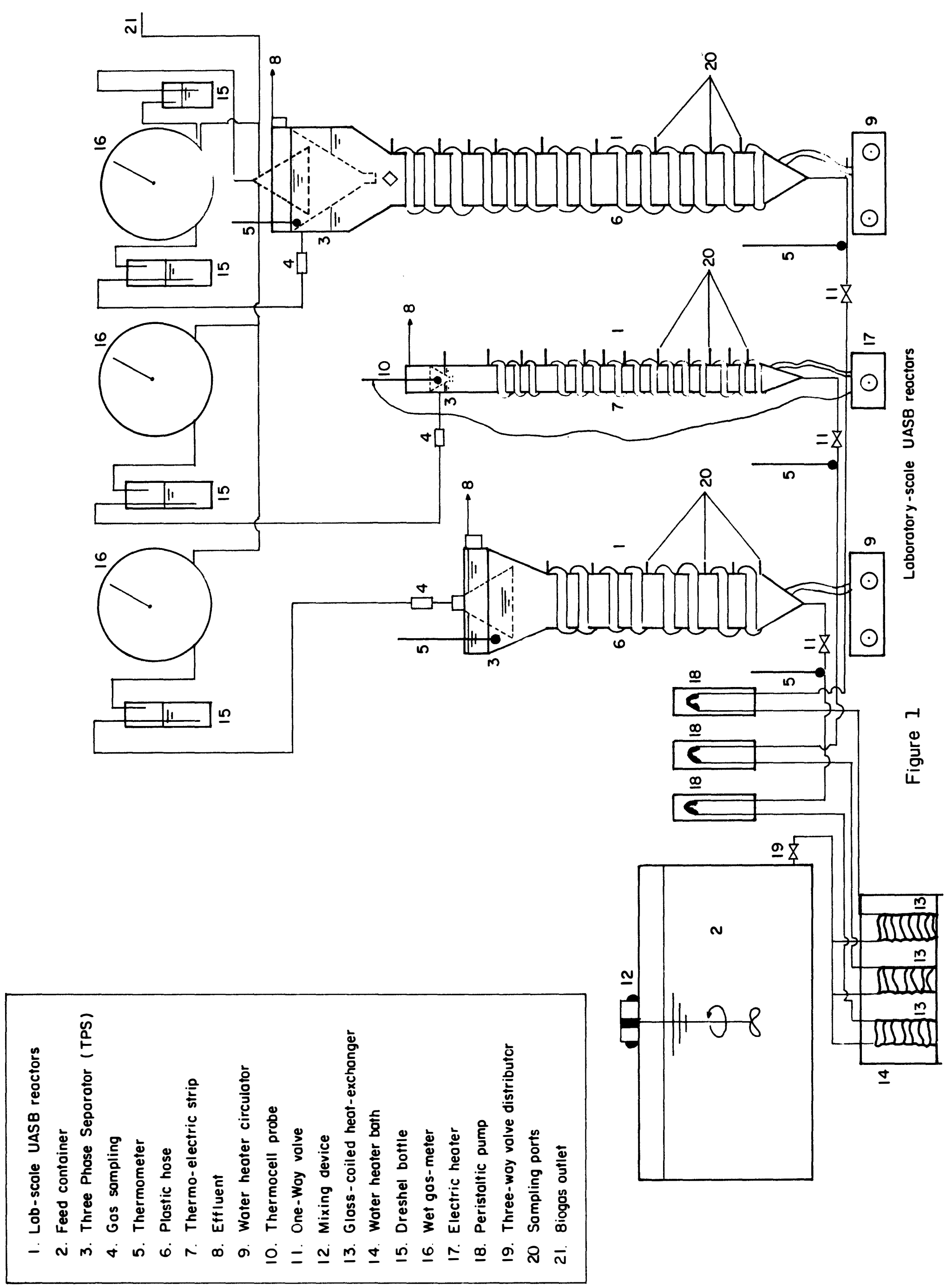

1. Lab-scale UASB reactors
2. Feed container
3. Three Phase Separator (TPS)
4. Gas sampling
5. Thermometer
6. Plastic hose
7. Thermo-electric strip
8. Effluent
9. Water heater circulator
10. Thermocell probe
11. One-Way valve
12. Mixing device
13. Glass-coiled heat-exchanger
14. Water heater bath
15. Dreshel bottle
16. Wet gas-meter
17. Electric heater
18. Peristaltic pump
19. Three-way valve distributor
20 Sampling ports
21. Biogas outlet
Laboratory-scale UASB reactors

Figure 1

RESULTS AND DISCUSSION

The Seed Sludge

The analysis of the sludge used to start-up the three UASB reactors took a significant length of time because of the SMA tests carried out. Among many purposes of using the SMA-test, in this research the most important were: (i) to quantify the specific methanogenic activity of the sludge using different substrates and therefore to classify approximately the bacterial consortia present; (ii) to measure the ability of the sludge to degrade a complex protein substrate; (iii) to assess the degree of compatibility between the spoilt beer waste and the seed sludge, and as a result, determine the best BLR that should be applied for the start-up. Three SMA-tests were carried out using, in each run, different types of substrate namely: (i) synthetic feed composition, using glucose as the main source of carbon; (ii) a mixture of volatile fatty acids composed of acetate, propionate, and butyrate; and (iii) spoilt beer waste. The SMA results are shown in Figure 2. The first run using synthetic substrate gave the highest SMA value of 0.081 l CH_4/g TVSS.day for BLR of 0.75 kg COD/kg TVSS, whereas a BLR of around 1.0 kg COD/kg TVSS overloaded the sludge, thus decreasing the SMA. The second SMA-test was carried out with the same sludge, but using a mixture of acetate, propionate and butyrate (about 600 mg/l of each). The maximum SMA was 0.056 l CH_4/g TVSS.day, and at a low BLR of about 0.25 kg COD/kg TVSS. With the increasing of the BLR the SMA even decreased. This suggests that the sludge was very poorly acclimatized with propionic acid, and therefore, with the increasing of BLR the SMA even decreased, showing signs of inhibition. The maximum SMA found for spoilt beer was about 0.091 l CH_4/g TVSS.day at a BLR of about 0.75 g COD/g VSS. However, in order to avoid any problem caused by inhibition, due to the high level of alcohol present in this type of substrate (650-1050 mg/l), the BLR applied was 0.12 kg COD/kg TVSS.day for all three reactors.

Start-up procedures

In this research the start-up period is defined as the length of time to achieve granulation. In order to impose different upflow velocities simultaneously in all three reactors, using the same hydraulic retention time (HRT), hydraulic loading rate (HLR) and volumetric loading rate (VLR), three UASB reactors were constructed with different designs as shown in Figure 1.

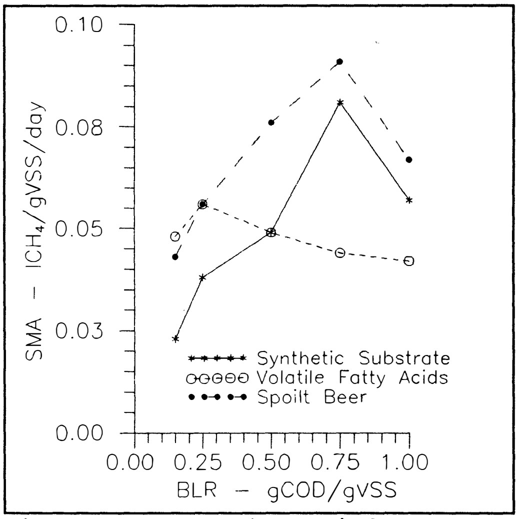
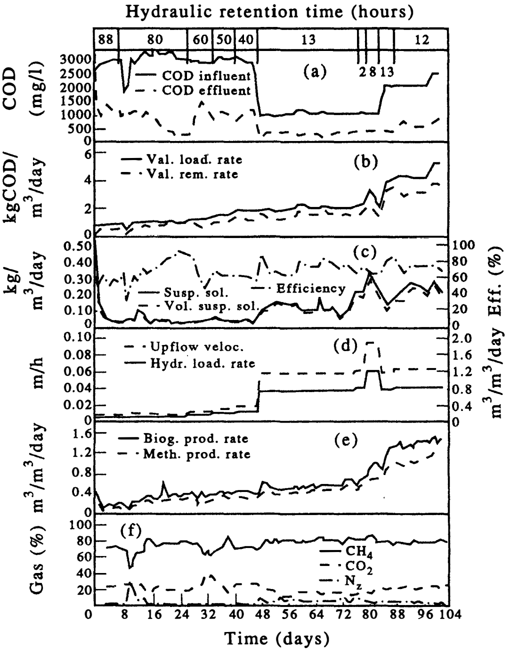


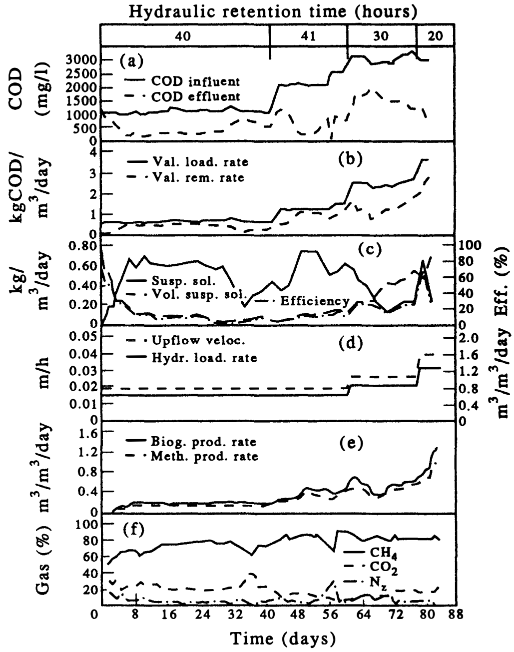
Figure 2 SMA-test applied to the seed sludge

Start-up of reactor 1

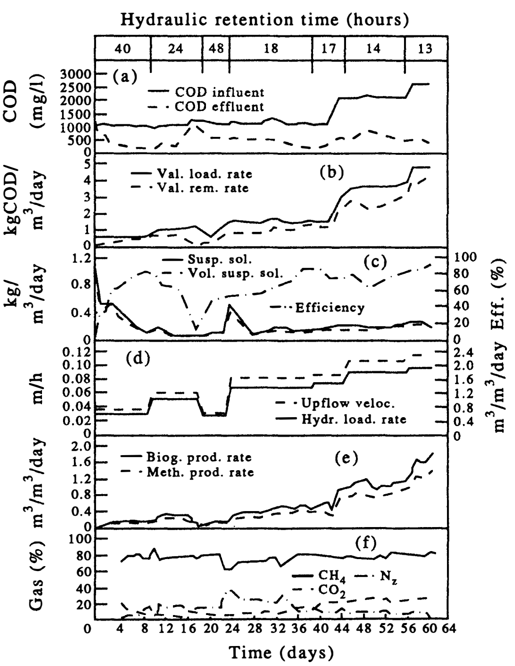
Reactor 1 was started-up with a COD of 3,000 mg/l. In order to maintain the BLR constant 0.12 kg COD/kg TVSS.day, the HRT was quite low at about 88 hours (Figure 3). After the first six days, despite the COD removal being quite poor (40%), the HRT was decreased to 80 hours to increase the mixing conditions via the ULV and to allow the reactor to wash out the scant biomass. This procedure improved the performance of the reactor and the COD removal reached about 74%. Until day 42, whereas the sludge was flocculent and quite dense, no granules had been formed by this time and the sludge activity was not high, with a methane yield of about 0.26 m^3 CH_4/kg COD_{rem}.day. This could be attributable to the high concentration of feed together with the poor quality of the biomass. In order to improve the sludge, the HLR was increased to allow a better selective process by



Obs: Granulation started on the 58th day



Obs: Granulation started on the 83rd day



Obs: Granulation started on the 42nd day

Figure 3. Reactor 1 (Start-up)
Figure 4. Reactor 2 (Start-up)
Figure 5. Reactor 3 (Start-up)

increasing mixing and wash-out of the poor biomass. To accomplish this objective, on the 49th day, the feed concentration was reduced to 1,000 mg/l and the VLR increased slightly from 1.86 to 2.0 kg COD/m^3.day, with an HRT of 13 hours. This reduction in HRT, from 40 to 13 hours, increased the ULV about three times and the biogas production per reactor unit volume also increased significantly, thus increasing the mixing conditions of the system and its performance. During this phase of investigation, on the 58th day, the first granules appeared in the bottom of the reactor; they had a well defined round shape and were up to 1.5 mm in diameter. The reactor took a further 50 days after granulation to reach the pre-established feed concentration of 3,000 mg COD/l, with a HRT of 16 hours. During this period a step-wise increment in the VLR was carried out by increasing the feeding concentration.

Start-up of reactor 2

Reactor 2 was started up having a COD of 1,000 mg/l and HRT of 40 hours (Figure 4). The BLR was the same, 0.12 kg COD/kg TVSS.day. Because of the diluted substrate the ULV during start-up was two times greater than reactor 1. The HRT was maintained in the same range (40 hours) for 42 days, and during this period the system behaved in an unstable manner, with an average COD removal of about 54%. To reach the desired concentration as quickly as possible, and also to increase gas production and mixing, the VLR was doubled on day 43 by increasing the feed concentration, from 1,000 to 2,000 mg/l. This change was beneficial for the system and the average COD removal increased to 69%. On day 58 and day 62 the feed concentration was increased to 2,500 and 3,000 mg/l respectively. Granules first appeared on day 83, presenting a more grey colour than those of reactor 1, and smaller in size. In this start-up, granulation was achieved after a very long period, possibly caused by the fast increases in feed concentration, in turn building up the volatile acids level in the system which would inhibit and stress the biomass. Also the mixing characteristics of this reactor were shown to be more plug-flow than in the other two, therefore, this system was more likely to have had different micro-environments (microzones), that could possibly have caused more hydrogen partial pressure in some areas than in others, as reported by Sam-Soon et al., (1987), and thus may possibly have affected the biomass characteristics and its performance.

Start-up of reactor 3

This reactor was started-up with the same BLR as the others, and with a COD concentration of 1,000 mg/l (as reactor 2). However the ULV, due to the design, was doubled. In this start-up the main objective was to check the increase in the VLR by decreasing the HRT, instead of increasing the feed concentration. This emphasises the effect of the ULV on the biomass. An HRT of 40 hours was applied during the first ten days. During the first stage of the start-up, the VLR was adjusted according to the performance of the reactor. On day 40, because of the good performance, the HRT was decreased to 17 hours, and during this stage, on day 42, the biomass started to become granulated, improving the performance significantly (see Figure 5). Immediately after the appearance of the granules, on day 43, the feed concentration was increased from 1,000 to 2,000 mg COD/l, doubling the VLR with only a small decrease in efficiency, and fifteen days later it was possible to achieve a feed concentration of about 2,500 mg COD/l with HRT of 13 hours. During this period the average COD removal efficiency increased from 71 to 83%. The required COD concentration of 3,000 mg/l was reached on day 62 with an HRT of 16 hours. This reactor showed an excellent performance during the start-up with a methane yield normally in excess of 0.30 m^3 CH_4/kg COD_{rem}.day, and took only a short period to achieve granulation. As a result it could be considered the best start-up criterion applied for starting up a UASB reactor in a short time period.

Performance of the UASB reactors during steady state

One of the main objectives in this work, as was said before, was to determine the effect of hydraulic forces and gas production rate on the start-up and steady-state periods. After the start-up, the performance of the reactors was observed measuring the COD removal efficiency, the rate of biogas produced by weight of biomass and the VSS concentration in the sludge. The SMA was also investigated along the profile using a new methodology (James et al., 1990).

The variation of the sludge bed volume compared with the total reactor volume, and the HRT in the sludge bed, for each steady-state condition achieved, is shown in Figures 6 and 7 respectively. It can be observed that the sludge bed growth was normally related to the decrease in HRT for reactor 1 and 3, whereas for reactor 2 the sludge bed volume decreased with the reduction in HRT from 6 to 4 hours. It can also be observed from Figure 7 that reactor 2 had an HRT in the bed sludge (for HRT in the reactor < 10 hours) always smaller than the other two reactors; this explains the low tability of this system.

In order to check the effect of ULV on the biomass, the kinetic parameters were determined for all three reactors. To obtain a reliable set of kinetic parameters, the UASB reactors were operated under steady-state conditions at eight different HRTs, namely 16, 14,12, 10, 8, 6, 4, and 2 hours. For each steady-state period five profiles of solids were withdrawn in order to minimize the errors. Due to the size of the lab-reactors, mainly reactor 2 (2.9 l), the interval period and the amount of sludge withdrawn should be well planned in order to avoid instability of the process. Because of all these procedures the experiment took a long length of time, about 630 days. The kinetic equations were determined through a mass balance equation of microorganisms and substrate in the chemostat. Many kinetic equations describing the biochemical reactions were reduced to linear form, and then, graphical techniques were employed to determine those values. Table 2 shows the summary of the kinetic parameters determined.

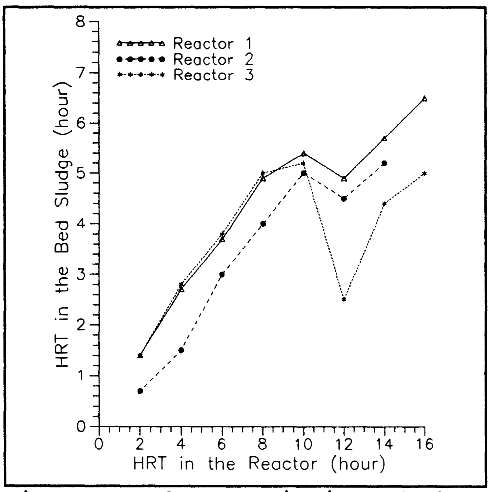


Figure 6 Volume variation of the sludge bed with the HRT

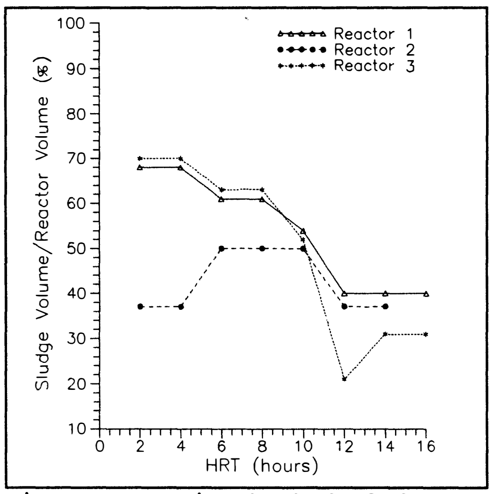


Figure 7 HRT in the bed sludge compared with the HRT of the reactor

The kinetics studies revealed that although the reactors were started up with the same type of seed sludge, each reactor developed a granulated biomass with different kinetic coefficients. This appears to have been caused by the selective physical forces imposed on the system, in particular the ULV and gas production rate per unit cross-sectional area of the reactor. A sensitivity analysis was carried out, and it was found that the kinetic parameter which may cause the greatest changes in the effluent substrate concentration is μ_{max}, followed by K_d and K_s.

TABLE 2 Monod Kinetic Coefficients of Reactors 1, 2 and 3

Reactor	Y	K_s	k	μ_{max}	K_d
1	0.1089	279.8	1.29	0.14	0.035
2	0.0909	429.7	2.79	1.10	0.028
3	0.1922	90.5	1.10	0.21	0.065

Y=mg VSS/mg COD, K_s=mg COD/l, k=mg COD/mgVSS.day, μ_{max}=1/day, K_d=1/day

CONCLUSIONS

The SMA-test should be carried out before the start-up procedure in order to: (i) quantify the SMA of the sludge; (ii) assess the potential of the sludge in degrading the waste; and (iii) determine the BLR to be applied to start-up.
From the three different procedures applied for starting up the three UASB reactors, the most important conclusions that should be stressed to achieve granulation, with a non-toxic soluble medium COD concentration waste, are:

(i) the start-up should preferably be carried out with a medium concentration substrate (around 1,000 mg COD/l) to allow a high HLR and therefore a high ULV;
(ii) the VLR should, if possible, be increased by decreasing only the HRT instead of increasing the COD concentration. This procedure allows the washout of the poor sludge, and the improvement of the mixing characteristics of the system; and
(iii) the predetermined level of substrate concentration, if greater than 2,000 mg/l, should be achieved only after granules have been formed.

After analysis of the three reactors, it was found that the best start-up method was that applied to reactor 3. The ULV was greater in this reactor than others, which resulted in a better selective process for the sludge, as well as an improvement in the mixing characteristics of the reactor. This reactor achieved granulation faster than others, and became the most stable and efficient during the subsequent experimental period. The best ULV for starting up was shown to be in the range of 0.72 to 0.96 m/day. It was found that the two reactors which operated with nearly the same ULV had close yield values, 0.109 and 0.091 per day for reactor 1 and 2 respectively, while the reactor 3, which was operated at double the ULV of the other two, had a yield value of 0.192 per day. These results indicated that the ULV has considerable effect on the sludge cultivated in the system, thereby acting as a selection process for the biomass.

Sensitivity analysis on the kinetic parameters indicated that μ_{max} is the most sensitive kinetic parameter. Therefore care should be exercised when this coefficient is used for modelling purposes.

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