ROBUSTNESS OF UASB REACTORS TREATING SEWAGE UNDER TROPICAL CONDITIONS

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To Sandra and Rodrigo, my safe harbours.

ABSTRACT

This PhD thesis presents results and discussions to elucidate the matters of performance and robustness of the Upflow Anaerobic Sludge Blanket (UASB) reactors for the treatment of municipal wastewater in tropical countries. The research focuses on the main operational parameters (hydraulic retention time -HRT, influent COD concentration - COD_{Inf}, organic loading rate - OLR, and sludge retention time - SRT) that affect the UASB loading potentials and its performance in "steady state" conditions, and on the response of the system when submitted to transient conditions.

The experimental investigation was performed using 11 pilot-scale UASB reactors (120 L) which were organised into three sets: Set 1, five reactors were operated with the same hydraulic retention time (HRT = 6 h) and different COD_{Inf}, ranging from 92 to 816 mg/L. Set 2, four reactors were operated with approximately the same COD_{Inf} (~800 mg/L), but with different HRTs, ranging from 1 to 6 hours. Set 3, the HRTs were identical to the second phase but the COD_{Inf} was adapted to have approximately the same OLR in the four reactors (~3.3 kgCOD/m^3.day).

In the first experimental part of the research, data was collected in order to evaluate the "steady state" performance and robustness of UASB reactors on the basis of COD removal efficiency, effluent variability, and pH stability. After the "steady state" condition was achieved, the sludge of each reactor was tested in terms of Specific Methanogenic Activity (SMA), biodegradability, settleability and, expansibility. In the second part of the experimental research, the robustness and stability of the system were evaluated under hydraulic and organic shock loads. Four indicators were defined for that purpose: COD removal efficiency, effluent variability, pH stability, and recovery time.

Under "steady state" conditions, UASB reactors can treat sewage with COD as low as 200 mg/L, and HRT as low as 2 h, but the maximum efficiency is achieved with an HRT longer than 4h, and COD_{Inf} higher than 300 mg/L. Effluent variability is highly dependent on the influent variability, showing that the reactors do not attenuate the daily fluctuation of the COD_{Inf}. UASB reactors treating sewage in tropical countries are extremely stable with regards to pH and buffer capacity. With regards to the biological properties of the sludge, the reactors operated with a short HRT produce sludge with a high SMA. Moreover, sludge of reactors operated with a long HRT and with a low COD_{Inf} resulted in low biodegradability. With respect to the hydrodynamic characteristics of the sludge, reactors operated with a high COD_{Inf} and/or a short HRT produced sludges with high settleability and low expansibility. Results show that it is useless to design a UASB reactor with a longer HRT to cope with organic or hydraulic shock loads.

Under shock load conditions the reactors resulted in COD removal efficiencies in the same range as during "steady state" conditions. The effluent COD fluctuates in the same range of the COD_{Inf} variation, showing that the reactors are unable to attenuate strong variation in the OLR. The recovery time from a shock load is always very short, as the reactors needed less than 18 hours after the shock ceased to resume performance. The reactors showed signals that they would acidify if the organic shock load continued. However, hydraulic shock loads barely affected the pH stability of the reactors.

Finally, the results obtained during this study showed that this kind of reactor is very robust with regards to the COD removal efficiency, as it keeps its maximum performance, in either "steady state" or transient conditions. Regarding to the pH stability, the UASB reactors also demonstrated extraordinary robustness, even when they are operated under extreme operational situations, which rarely occur in municipal wastewater treatment plants. When a shock load is imposed they need a very short time to recover. However, the UASB reactors are not robust with regard to effluent variability. Regarding this matter, the robustness of the reactors can be improved with the implementation of a secondary settler.

TABLE OF CONTENTS

1

GENERAL INTRODUCTION AND SCOPE OF THE THESIS

Despite vast amount of literature dealing with the treatment of municipal wastewater using Upflow Anaerobic Sludge Blanket (UASB) reactors, there are still some unclear aspects which need to be explained, viz. the operational limit of the reactors to achieve a "steady state" condition; the factors that affect or control the sludge retention time; the factors affecting the methanogenic activity and biodegradability of the sludge in UASB reactors treating sewage; the effect of the operational parameters, viz. hydraulic retention time and influent COD concentration, on the sludge settleability and expansibility; and the capacity of anaerobic wastewater treatment systems to cope with extreme variations in imposed organic and hydraulic loads.

This PhD thesis intends to investigate the aforementioned matters, and produce experimental results that will clearly establish the degree of robustness of UASB reactors in the treatment of municipal wastewater in tropical countries. The entire experimental investigation was carried out using 11 pilot-scale UASB reactors that were fed with raw sewage and operated with different sets of hydraulic retention times and influent concentrations. The research focuses on the main operational parameters affecting the UASB loading and its performance in a steady state (flow rate, influent concentration and organic loading rate), and on the response of the system when submitted to transient conditions.

1.1. INTRODUCTION

Human societies produce wastes that can represent a useful raw material for the production of energy, and the recovery of by-products and component water. Several techniques are already available to attain the goals of "Environmental Protection and Resource Conservation" (Lettinga et al., 2000). In the case of wastewater treatment, combinations of different methods can be used, viz. physical, chemical, and biological. The last method can be divided into two classes (aerobic and anaerobic) which constitute the main units of most wastewater treatment plants.

Aerobic processes, which are widely used for the treatment of wastewater, have at least two distinct disadvantages: their relatively high-energy requirement and high excess sludge production, which requires handling, treatment and disposal. In contrast, anaerobic processes generate energy in the form of biogas, and produce sludge in significantly lower amounts than those resulting from aerobic systems (Lettinga, 1996). Surprisingly, a certain prejudice exists against the use of anaerobic processes, particularly concerning the use in centralised plants which treat municipal wastewater in tropical countries. The reasons against anaerobic processes are many, and some are relevant while others are quite questionable. Reasons for rejecting the concept include odours, lack of budget for maintenance, lack of skilled labour, and sensibility of the reactors to the operational flaws. Some of these reasons are undoubtedly political or commercial and it is difficult to eliminate them on the basis of scientific work. Other reasons result from a serious lack of knowledge by the engineers on the design and operation of these systems.

According to the supporters of anaerobic wastewater treatment (AnWT), these systems have low investment costs, generally consume little energy and other resources, and produce methane that can be used for energy production. Moreover, the excess sludge production is very low and generally well stabilised. The nutrient requirements are minimal, and in many cases, AnWT systems can accommodate, when well designed, very high space loads. An additional important benefit is that anaerobic sludge can be preserved while not being fed for long periods of time at temperatures below 15^{o}C. It has also been well demonstrated that the anaerobic process is capable of treating almost all types of industrial wastewater as well as sewage (van Lier and Boncz, 2001; Lettinga *et al.*, 1997; Alaerts *et al.*, 1993; and Lettinga et al., 1980).

Considering this matter objectively, it might appear that both defenders of the aerobic and anaerobic processes actually overestimate their potential and underestimate their weakness; or at least they may fail to see the flaws of the system they favour. This behaviour is sociologically explainable as scientists and engineers tend to defend their professional background, turning it into "the best in the world" for their own benefit. In general, a treatment system that combines the advantages of both treatment systems would be more efficient (Gijzen, 2001; and Wiegant, 2001). Anaerobic processes are the cheapest method for treatment of wastewater, but their effluent cannot achieve most discharge standards. However, aerobic processes as post-treatment can be designed for lower loading rate, and consequently lower costs.

Reasons against the implementation of anaerobic processes that have been provided by some established wastewater treatment companies in the Northeast Region of Brazil (tropical conditions) focus on three main points: (1) anaerobic reactors spread unpleasant odour; (2) anaerobic reactors are unstable; and (3) high performance reactors such as the Upflow Anaerobic Sludge Blanket (UASB) reactors cannot cope with high load rate variations. In order to contest the first two arguments, the example of Curitiba (a city in southern Brazil) is presented here (Aisse *et al.*, 2000). Several anaerobic reactors have been put into operation in densely inhabited areas of Curitiba. They have performed satisfactorily for many years, i.e. they perform without any problems of odours or instability, even in the relatively adverse climatic conditions of Curitiba, with its average air temperatures varying annually from 5 to 25^{o}C. However, it seems that there is still not enough explicit experimental information available to confirm or rebut the third point, i.e. that the UASB reactors would be very sensitive to variations on the flow and/or concentration.

Therefore, most of the bottlenecks are related to system robustness and reliability under extreme environmental and operational conditions.

The notion of robustness of the anaerobic reactors is still rather confusing. Robustness should be defined as the capacity of the treatment systems to reach a stable steady state under certain environmental and operational conditions. However, robustness should also be defined in terms of variability of the final product of the process, i.e. the effluent. Furthermore, robustness should be defined as the capacity of a system to cope with more severe environmental and operational variations. In fact, the presumed incapacity of the anaerobic reactors to withstand environmental and operational variations still causes serious problems of reliability, and has led to a certain prejudice on the use of this system for treatment of municipal sewage.

Despite vast literature dealing with the treatment of municipal wastewater using UASB system, there still remain some unclear aspects which need to be elucidated, viz.:

(i) The operational limit of reactors to achieve “steady state” condition.

(ii) The factors that affect or control the SRT. This is important as the SRT comprises one of the most important factors in determining the loading potentials and the performance of an UASB reactor;

(iii) The factors affecting the methanogenic activity of the sludge in UASB reactors treating sewage;

(iv) The effects of the operational conditions on the biodegradability of the sludge of UASB reactors;

(v) The effect of the operational parameters, viz. HRT and influent COD concentration, on the sludge settleability;

(vi) The assessment of the relationship between the hydraulic shock strength and the sludge bed expansion, as well as the effect of several other operational parameters on the dynamic behaviour of the sludge bed;

(vii) The assessment of the capacity of AnWT systems to cope with extreme variations of organic and hydraulic loads and environmental conditions, as there are still researchers who postulate that UASB reactors inherently suffer from instability due to high variations of organic or hydraulic loads. For this purpose, an assessment of the limit of the UASB reactors with respect to shock loads is needed, within a well-organised set of experiments. This appears to be a method which will definitively eliminate these prejudices.

1.2. SCOPE OF THE THESIS

This PhD thesis intends to investigate the aforementioned matters and produce experimental results that will clearly establish the degree of robustness of the UASB reactors for the treatment of municipal wastewater in tropical countries. The whole experimental investigation was carried out using 11 pilot-scale UASB reactors, fed with raw sewage and operated with different sets of hydraulic retention times and influent concentrations. The research focuses on the main operational parameters affecting the UASB loading and its performance in a steady state (flow rate, influent concentration and organic loading rate), and on the response of the system when submitted to transient conditions.

The structure of this thesis is presented in Figure 1.1. This first chapter introduced the problems which still need to be elucidated in order to improve the implementation of the UASB reactors for the treatment of municipal wastewater. The experimental work is divided into two parts: The fist part (Chapters 2, 3, and 4) deals with the operation of UASB reactors under “steady state” conditions, while the second (Chapter 5 and 6) deals with the operations under shock load conditions. Chapter 2 describes experiments that clarify the influence of influent concentration and flow rate on the performance of the UASB reactors. Chapter 3 describes the relationships between the operational parameters and the specific methanogenic activity and biodegradability of the sludge obtained from the mentioned reactors. Chapter 4 describes short-term experiments, using the sludge obtained from the mentioned reactors to assess the hydrodynamic behaviour of the sludge bed concerning to settleability and expansion. Chapter 5 presents a literature review about the effect of the operational and environmental variations on the performance of anaerobic reactors. The experiments for the assessment of the stability of the UASB reactor during transient conditions are described in Chapter 6. The final chapters summarise the whole research and draws conclusion and recommendations for design, operation and future research.

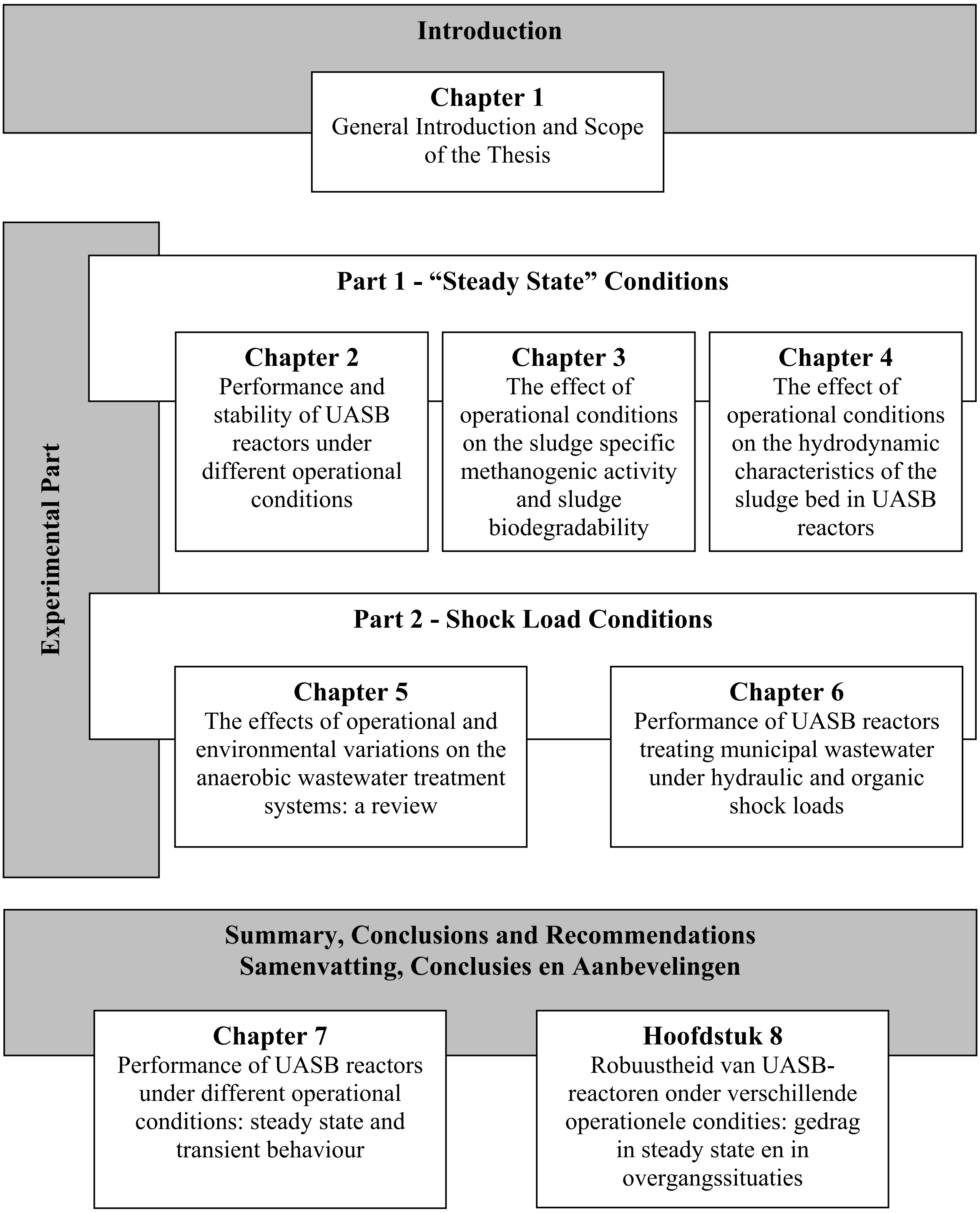

Figure 1.1 – Plan of the Thesis

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PART 1 - “STEADY STATE” CONDITIONS

2

PERFORMANCE AND STABILITY OF UASB REACTORS UNDER DIFFERENT OPERATIONAL CONDITIONS

In this investigation, experimental data was collected in order to evaluate the performance of Upflow Anaerobic Sludge Blanket (UASB) reactors when treating municipal wastewater on the basis of (i) COD removal efficiency, (ii) effluent variability, and (iii) pH stability during a (pseudo) steady state. The experimental investigation was performed using 11 pilot-scale UASB reactors (120L) which were divided into three sets: In Set 1, five reactors were operated with the same hydraulic retention time - HRT (6 h) and different influent COD concentrations, ranging from 92 to 816mg/L. In Set 2, four reactors were operated with approximately the same influent COD concentration (COD_{Inf}~800mg/L), but with different HRTs, ranging from 1 to 6 hours. In Set 3, the HRTs were identical to Set 2 but the COD_{Inf} was adapted to have approximately the same organic loading rate (OLR) in the four reactors (approximately 3.3 kgCOD/m^3.day). The results show that decreasing the COD_{Inf}, and/or lowering the HRT, leads to decreased efficiencies as well as increased effluent variability and reactor instability. During this experiment, the UASB reactors could efficiently treat sewage with a concentration as low as 200mgCOD/L. It was also established that they could be operated satisfactorily at an HRT as low as 2 hours, without problems of operational stability. The maximum COD removal efficiency can be achieved at influent concentrations exceeding 300mgCOD/L and HRT of 6 hours.

2.1. INTRODUCTION

The feasibility of Upflow Anaerobic Sludge Blanket (UASB) reactors for adequate sewage treatment has been amply demonstrated at both pilot and full-scale installations (van Haandel and Lettinga, 1994; Vieira *et al.*, 1994; Schellinkhout and Collazos, 1992; and Haskoning *et al.*, 1985). In general, hydraulic retention times (HRT) of 4 to 8 hours are most commonly applied in full-scale plants (Cavalcanti *et al.*, 1999). However, in order to assess the effects on performance, pilot plants have been operated with much shorter HRTs (1.0 to 3.5h), resulting in total COD (chemical oxygen demand) removal efficiencies in the range of 16 to 34% (van der Last and Lettinga, 1992).

The design of the UASB reactor is determined by parameters including hydraulic load, superficial biogas velocity, sludge retention time (SRT), as well as operational temperature (Wiegant, 2001). The HRT, upflow velocity (V_{up}) as well as influent COD concentration (COD_{Inf}) and composition comprise the most important parameters for the design and evaluation of these systems when used for the treatment of municipal wastewater in tropical countries (Wiegant, 2001; Vieira and Garcia Jr., 1992; and Souza, 1986). One of the most attractive points of an UASB reactor is its potential to be operated with a short HRT, permitting the construction of compact units which will significantly reduce the investment costs. However, an excessive reduction in the HRT will lead to the reduced performance of UASB reactors. This is due to the extremely short contact time between the sludge bed and the substrate, sludge washout, as well as the decreased filtration capacity of the sludge bed at higher upflow velocities. Moreover, the reduced HRT may also lead to the disintegration of granules or flocks under the abrasive action of shear forces (Mahmoud, 2002; O'Flaherty *et al.*, 1997; and Kosaric *et al.*, 1990), and causes an incomplete hydrolysis of particulate matter and the consequent accumulation of this material in the reactor, which in turn leads to an increased sludge production.

Gonçalves *et al.* (1994) considered upflow velocity as the main parameter that influenced the entrapment of suspended solids (SS). However, in their studies with a fermentation reactor, the SS removal efficiencies did not substantially decrease, viz. from 60% to 50% within the V_{up} range of 0.6 – 3.2 m/h (HRT ranging from 4.4 to 1.1h). Vieira and Garcia Jr. (1992) also found there to be no distinct effect of the HRT on the treatment efficiency within the range of 4.4 to 14.5 hours (V_{up} between 0.4 and 1.3m/h). In contrast, van Haandel and Lettinga (1994) reported an increase in the SS removal efficiency with increasing HRT, and consequently decreasing V_{up}. The differences among the conclusions from several investigations can be attributed to distinct reactor design, operational procedures and studied HRT range (and V_{up}).

With regard to the applicable influent COD concentration, Rittmann and McCarty (1980a,b) and Jewell (1987) proposed a value for the minimum influent concentration which an anaerobic system can treat at a steady state condition. They operated an anaerobic biofilm reactor fed with acetate at 35^{o}C, and found that the biofilm activity becomes negligible below 3.7mgBOD/L. The latter researchers included only biomass decay as a loss mechanism, while it is known that sloughing due to shear forces can be an important factor that determines the steady state of the biofilm (Rittmann, 1981). Kato (1994), using lab-scale UASB reactors fed with ethanol, concluded that influent concentrations below 200mgCOD/L led to a very poor performance of the reactor. Wang (1994) found that the influent concentration had a remarkable effect on the treatment efficiency, but it is not clear from his work whether the reactors adapted to the imposed operational conditions. Seghezzo *et al*, (2002) investigated pilot-scale UASB reactors operated with an HRT of 6 hours, fed with sewage which had a very low concentration (total COD=153mg/L). They reported efficiencies of up to 55%, which is very high when taking into account the relatively low liquid temperature of around 17^{o}C during some months per year. Halalsheh (2002) investigated the potential of UASB reactors in treating strong domestic wastewater (COD_{Inf}=1500mg/L) with a high fraction of suspended organic solids (up to 80%). The reactor was operated without sludge discharge, with an HRT of approximately 24 hours and an OLR of approximately 1.5 kgCOD/m^3.day. Despite the comparatively long HRT, the total COD removal efficiency of the reactor was only 62% during summer time (with temperatures around 25^{o}C). The relatively low efficiency was mainly due to the sludge washout. In the case of Seghezzo *et al.* (2002) and Halalsheh (2002) the influence of different influent COD on the performance of anaerobic reactors was not the focal point of their research. However, their works are still good examples of UASB reactor behaviour when treating domestic sewage under extreme conditions.

Even though advantages of using anaerobic systems for pre-treatment of wastewater are recognised, concerns about reactor stability and effluent variability still exist. With respect to reactor operational stability, there are currently a large number of papers reporting the results of anaerobic treatment of domestic sewage. However, each paper refers to a strict range of operational conditions, making it difficult to compare the different investigations. Moreover, only limited data is available for UASB reactors treating sewage under extreme conditions, e.g. very short hydraulic retention times or low influent concentrations. Most of the reported results refer to anaerobic systems operated with HRTs within a range of 4 to 10h for operational temperatures higher than 20^{o}C, and 6 to 14h for temperatures lower than 20^{o}C (Kalogo and Verstraete, 1999; Foresti, 2001; and Seghezzo *et al.*, 1998). Thus, the operational limit of UASB reactors for the treatment of municipal wastewater is still not clear. With regards to effluent variability, very few studies directly deal with this subject, and no reports which focused on the effect of operational procedures on the fluctuation of the effluent concentration were found. Kennedy and Hamoda (1994) investigated an anaerobic downflow fixed film reactor that was fed with sucrose and operated at constant OLR and temperature. They concluded that effluent variability is intrinsic to that kind of reactor.

In this work, experimental data was collected in order to evaluate the influence of the influent COD and the hydraulic retention time on the performance of UASB reactors treating sewage. This data covered a wide range of both HRT and COD_{Inf} values. The performance is evaluated on the basis of (i) COD removal efficiency, (ii) effluent variability, and (iii) operational pH stability during a (pseudo) steady state. To achieve this goal, three sets of pilot-scale UASB reactors were operated until "steady state" conditions were established, each with different hydraulic retention times and influent concentrations.

2.2. MATERIAL AND METHODS

2.2.1. Experimental Set-Up

The experimental investigation was carried out utilising 11 pilot-scale UASB reactors fed with pre-screened domestic sewage. The reactors were built using PVC tubes with a working volume of 120L, a height of 4.0m and internal diameter of 0.20m. They had a modified gas-solid-liquid separator as described by Cavalcanti (2003), and were equipped with dosing pumps, gas samplers, and 14 sludge collection points.

Methane production was monitored using a Mariotte bottle with 120L of volume, filled with a NaOH solution (5%w/w). A very slow stirrer (1rpm) was installed in the reactor to avoid channelling and "piston" formation in its sludge bed (rising sludge due to entrapped biogas in the sludge layer) – Gonçalves *et al.* (1994) also used this approach. Figure 2.1 shows a schematic diagram of the pilot-scale reactors used in our experiments.

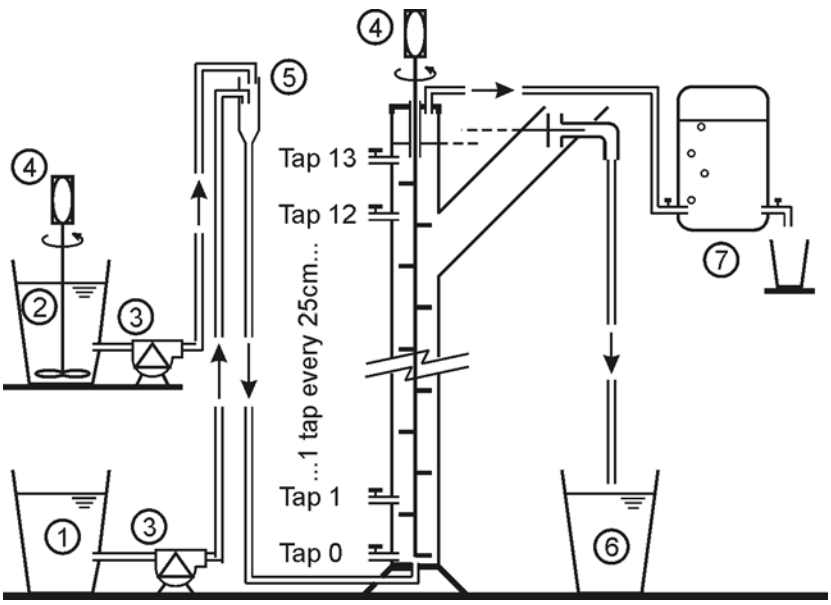

Figure 2.1 – Schematic diagram of the pilot-scale UASB reactors.

Legend:
(1) Water tank,
(2) Sewage tank,
(3) Dosing pumps,
(4) Stirrer,
(5) Feeder,
(6) Effluent tank,
(7) Marriotte bottle.

2.2.2. UASB Reactors Start-Up and Operation

The pilot-scale reactors were inoculated with anaerobic sludge discharged from a $5m^3$-UASB reactor. This $5m^3$-UASB reactor had been operated for more than five years with raw sewage, and with an HRT of 6 hours. The pilot-scale reactors were filled to the top with this sludge, and then operation was started at a constant flow and having a particular influent COD. All excess sludge was washed out during the first few days of the experimental period. The remaining sludge represented the maximum biomass accumulation of the reactors, under those specific imposed conditions. During the entire period of operation, there was no intentional sludge discharge, and sludge production was evaluated from the sludge mass carried by the effluent. The air temperature was within the range of 25°C±7 and liquid temperature was 27°C±1. The operational parameters are presented in Table 2.1. The reactors operated in this work were denominated by R^{HRT}_{COD} (column 1), where the superscript index stands for the hydraulic retention time, and the subscript index stands for the total influent COD, both being the average during the “steady state” conditions.

Table 2.1 – Operational parameters.

Reactor	HRT (h)	Vup (m/h)	COD_{Inf} (mg/L)	OLR ($kgCOD/m^3.day$)
------ Set 1 - UASB reactors operated with the **same HRT**, but different COD_{Inf} and OLR. ------				
R^6_{816}	**6**	**0.64**	816±45	3.3±0.2
R^6_{555}	**6**	**0.64**	555±36	2.2±0.1
R^6_{298}	**6**	**0.64**	298±19	1.2±0.1
R^6_{195}	**6**	**0.64**	195±15	0.8±0.1
R^6_{92}	**6**	**0.64**	92±10	0.4±0.0
------ Set 2 - UASB reactors operated with **similar COD_{Inf}**, but different HRT and OLR. ------				
R^6_{816}	6	0.64	**816±45**	3.3±0.2
R^4_{770}	4	0.95	**770±38**	4.6±0.2
R^2_{787}	2	1.90	**787±31**	9.4±0.4
R^1_{716}	1	3.80	**716±42**	17.6±1.2
------ Set 3 - UASB reactors operated with **similar OLR**, but different HRT and COD_{Inf}. ------				
R^6_{816}	6	0.64	816±45	**3.3±0.2**
R^4_{558}	4	0.95	558±31	**4.2±0.2**
R^2_{352}	2	1.90	352±18	**3.4±0.2**
R^1_{136}	1	3.80	136±18	**3.3±0.4**

Reactor R^6_{816} is repeated to create the three sets above. ± values are Confidence Intervals (α=0.05)

The 11 pilot-scale UASB reactors were divided into three sets. In Set 1, five reactors were fed at a constant flow of 20 L/h (HRT=6h) and with different COD_{Inf}. In Set 2, four reactors were operated with approximately the same COD_{Inf} (~800mg/L), but with different HRTs. In Set 3, HRTs were identical to Set 2 but the COD_{Inf} was adapted to have approximately the same organic loading rate (OLR~3.3 kgCOD/m^3.day) in the four reactors. Some of the reactors were operated at extreme conditions for long periods, i.e. with very short HRT and/or fed with very low influent concentration, or with very high OLR for the treatment of domestic sewage. This was only relevant for research purposes, as these conditions are not realistic except for short-term (peak hours) or calamity situations.

The reactor performance and stability were evaluated based on COD removal efficiency (Equations 2.1 and 2.2), SS removal efficiency (Equations 2.3 and 2.4), gas production, specific methanogenic activity (SMA), maximum sludge accumulation, sludge retention time - SRT (Equation 2.5), hydrolysis, acidification and methanisation, in addition to both influent and effluent solids, VFA, pH and alkalinity. The COD removal efficiency was expressed in two ways: (i) total effluent/total influent ratio (Equation 2.1), and (ii) settled effluent/total influent ratio, after 1 hour of settling time (Equation 2.2). The first ratio represents the overall removal efficiency, and the second indicates the treatment potential that could be attained if efficient settling would be applied and excess sludge was discharged from the UASB reactor, or if a secondary settler would have been installed. This approach was also used by Barbosa and Sant'Anna Jr. (1989) and Cavalcanti *et al.* (1999).

$$E_{Tot} = \left(1 - COD_{Eff}^{Tot} / COD_{Inf}^{Tot}\right) \times 100 \qquad \text{(Eq. 2.1)}$$

$$E_{Set} = \left(1 - COD_{Eff}^{Set} / COD_{Inf}^{Tot}\right) \times 100 \qquad \text{(Eq. 2.2)}$$

Where: E_{Tot} is the COD removal efficiency based on total effluent COD; E_{Set} is the COD removal efficiency based on settled effluent COD; COD_{Inf}^{Tot} is the total influent COD; COD_{Eff}^{Tot} is the total effluent COD; and COD_{Eff}^{Set} is the settled effluent COD. The efficiencies are in % and the COD in mg/L.

For the assessment of SS removal efficiency, two approaches were considered:

(i) The first approach is to assume that all effluent suspended solids that settled after one hour represent excess sludge, and only the non-settleable suspended COD fraction in the effluent is accounted for in the calculation of the SS removal efficiency. This can represent the ideal removal efficiency which occurs if all settleable sludge would be retained in the reactor, and if the reactor would be operated with intentional excess sludge discharge, or as mentioned before, if a secondary settler would have been installed. This SS removal efficiency was referred as E_{SS}^{Set} (Equation 2.3).

(ii) The second approach is to assume that the effluent SS is the summation of non-settleable and settleable effluent SS. This represents the worst situation that can occur, i.e. the reactors are operated with their maximum sludge accumulation capacity and without intentional excess sludge discharge, but also without a secondary settler for the removal of the excess sludge. This SS removal efficiency was referred as E_{SS}^{Tot} (Equation 2.4).

$$E_{SS}^{Set} = \left(1 - \left(COD_{Eff}^{Set} - COD_{Eff}^{Dis}\right) / COD_{Inf}^{SS}\right) \times 100 \qquad \text{(Eq. 2.3)}$$

$$E_{SS}^{Tot} = \left(1 - \left(COD_{Eff}^{SS} + COD_{Eff}^{X}\right) / COD_{Inf}^{SS}\right) \times 100 \qquad \text{(Eq. 2.4)}$$

Where: E_{SS}^{Set} is the SS removal efficiency based on the SS content (as COD) of the settled effluent; E_{SS}^{Tot} is the COD removal efficiency based on total SS effluent (as COD); COD_{Eff}^{Dis} is the dissolved COD fraction in the effluent; COD_{Inf}^{SS} is the influent SS (as COD); COD_{Eff}^{SS} is the effluent SS (as COD), COD_{Eff}^{X} is the excess sludge (as COD). The efficiencies are in % and the COD in mg/L.

It was assumed that the reactors had reached "steady state" conditions merely two weeks after inoculation. This is because the results of effluent COD presented the same pattern, i.e. approximately the same average COD concentration and the same range of variations during the whole operational period after the first two weeks. However, the experiments with the sludge bed (sludge profile), and sludge characteristics (methanogenic activity) were conducted at the end of the operational period. Most of the operational periods of the reactor lasted more than three times the SRT; except for reactors R^6_{298} and R^6_{195}, which were operated for more than twice the SRT, and reactor R^6_{92}, which could not be operated longer than 83 days and where the SRT was 558 days.

At the end of the operational period, the maximum sludge accumulation (mass in terms of volatile solids) inside each reactor was determined from the sludge concentration profile. The sludge profile was calculated using sludge samples withdrawn from the 14 taps installed along the reactors height (see Figure 2.1). SRT was calculated according to Cavalcanti (2003) (Equation 2.5), i.e. the ratio between the determined sludge VS mass (Equation 2.6) and the daily sludge production (calculated based on Equations 2.7 and 2.8).

Gas production, expressed at Standard Temperature and Pressure (STP), was eventually measured hourly over 24-hour periods, and samples were taken to determine gas composition. Gas production is calculated as gCOD-CH_4/L and includes the gas dissolved in the effluent.

$$SRT = M_X / (Q \times X_{Eff}) \quad \text{(Eq. 2.5)}$$

$$M_X = \sum_{n=0}^{n=13} x_n \times v_n \quad \text{(Eq. 2.6)}$$

$$X_{Eff} = COD_{Eff}^{X} / (1.5 \times 1000) \quad \text{(Eq. 2.7)}$$

$$COD_{Eff}^{X} = COD_{Eff}^{Tot} - COD_{Eff}^{Set} \quad \text{(Eq. 2.8)}$$

Where: SRT is the sludge retention time (day); M_X is the total mass of volatile solids in the sludge bed (gVS); Q is the flow rate (L/day); X_{Eff} is the sludge volatile solids concentration in the effluent (gVS/L); xn is the sludge volatile solids concentration in the sample taken from the sampling tap n ($0<n<13$) (gVS/L); vn is the volume of the sludge bed related to sampling tap n (L); $COD_{Eff}{}^{X}$ is COD due to settleable sludge in the effluent (mg/L). It was assumed that 1g of VS in the sludge is equivalent to 1.5g of COD (van Haandel and Lettinga, 1994; and Marais and Ekama, 1976).

2.2.3. Influent

The reactors were fed with the sewage of Campina Grande city - Brazil (350,000 inhabitants), which is a typical domestic wastewater. This sewage was withdrawn from the interceptor sewer directly into a plastic-net basket (2.25mm^2 square holes), in order to prevent the clogging of the pumps by coarse solids. The wastewater was stored in a tank with a capacity of 24 hours, and gently stirred to prevent sedimentation. The hourly variation of the sewage was thus avoided, and the reactors were fed with an almost constant influent each day. The main characteristics of this sewage are shown in Table 2.2. Some of the reactors were operated with a pre-screened sewage diluted with tap water using specific ratios of water to sewage, making it possible to achieve the required influent concentrations (see Table 2.1).

Table 2.2 – Characterisation of the raw sewage.

Parameter	Average	Stand. Dev.	Max. Value	Min. Value
COD (mg/L)	764	195	1363	125
TKN (mg/L)	58.3	13.4	97.4	28.6
Ammonia (mg/L)	43.1	10.0	71.7	19.6
Total Alkalinity (mg/L)	330	62	496	111
Total VFA (mg/L)	189	37	286	56
pH	7.2	0.3	7.9	6.5
TS (mg/L)	1051	310	1968	111
VS (mg/L)	432	182	1413	94

COD: Chemical Oxygen Demand, TKN: Total Kjeldahl Nitrogen, VFA: Volatile Fatty Acids, TS: Total Solids, VS: Volatile Solids.

2.2.4. Analytical Methods

All physical-chemical analyses were performed as recommended by APHA (1995). Raw samples were used for Total COD; filtered samples were performed through 4.4µm folded paper filters (Schleicher & Schuell 595½, Germany) for paper filtered COD; and through 0.45 µm membrane filters (Schleicher & Schuell ME 25, Germany) for dissolved COD. The micro-COD method was used for all COD analysis. Total VFA followed the procedure described in Buchauer (1998). Specific Methanogenic Activity (SMA) was determined following the laboratory protocols of the Department of Environmental Technology of Wageningen University (Chaggu, 2004). The suspended solids and colloidal fractions of the influent and effluent (expressed as COD) were calculated using Equations 2.9 and 2.10.

$$COD^{SS} = COD^{Tot} - COD^{PF} \quad \text{(Eq. 2.9)}$$

$$COD^{Col} = COD^{PF} - COD^{Dis} \quad \text{(Eq. 2.10)}$$

Where: COD^{SS} is the COD concentration due to total suspended solids; COD^{Col} is the COD concentration due to colloidal fraction of the sample; COD^{Dis} is the COD concentration due to dissolved fraction of the sample, determined through membrane filters; COD^{Tot} is the total COD of the influent or effluent; COD^{PF} is the filtered samples through paper filters. All COD concentrations are expressed in mg/L.

2.2.5. Statistics

Fluctuations in the effluent COD concentration and in the COD removal efficiency were evaluated based on the Coefficient of Variability (CV). This statistical parameter is used to compare different sets of data when their mean differ appreciably (Sokal and Rohlf, 1973). The CV is the standard deviation expressed as a percentage of the mean.

Statistical analysis of variance (ANOVA), as described by Sokal and Rohlf, 1973), was applied to the data obtained from the different reactors in order to assess whether operational conditions cause distinct effects on the performance of the reactors.

2.3. RESULTS AND DISCUSSION

The set-up of the experiment was planned to allow for the evaluation of the influence of operational parameters COD_{Inf}, HRT and OLR, on the UASB performance, based on treatment efficiency, effluent variability and reactor stability. The values of the main operational parameters and reactor response obtained from the entire research are presented in Table 2.3.

2.3.1. The Effect of Influent Concentration on Reactor Performance

Reactor Efficiency

Figure 2.2 depicts the COD removal efficiencies of the reactors operated at different influent COD and OLR, but with a similar HRT of 6 hours (Set 1). With influent concentrations lower than 300mgCOD/L, the efficiency of the UASB reactors decreases. However, with values exceeding 300mgCOD/L, the reactors achieved their maximum efficiency, viz. around 59% for total-effluent COD (Figure 2.2A) and around 77% for settled-effluent COD (Figure 2.2B). The Analysis of Variance showed that there were no significant differences (α=0.05) among reactors R^6_{816}, R^6_{555}, and R^6_{298} for COD removal efficiencies.

It was expected that low substrate concentrations would result in a decreased reactor performance due to the poor removal of suspended solids at smaller influent SS concentrations (Miron, 1997). This is because low influent suspended solids coincide with a low influent COD, decreasing the collision opportunity of the influent solids and the sludge bed (Mahmoud, 2002). Moreover, lower performance was also expected due to the mass transfer limitations at lower dissolved COD concentration. Even so, the UASB reactors were apparently able to treat sewage with an average COD_{Inf} as low as 92mg/L, with efficiencies higher than 66% (based on settled effluent).

Table 2.3 – Performance of the different UASB reactors.

Reactor	HRT	COD_{Inf}^{Tot}	COD_{Inf}^{SS}	OLR	COD_{Eff}^{Tot}	COD_{Eff}^{Set}	COD_{Eff}^{SS}	COD_{Eff}^{X}	COD_{CH4}	E_{Tot}	E_{Set}	E_{SS}^{Set}	Alk_{Eff}	VFA_{Eff}	M_X	SRT	Time
Set 1 - UASB reactors operated with the **same HRT**, but different COD_{Inf} and OLR.																	
R^6_{816}	**6**	816±45	566±28	3.3±0.2	343±23	177±10	38±8	166±21	472	57.0±2.7	76.6±1.1	93.3	393±41	49±17	2.104	49	226
R^6_{555}	**6**	555±36	421±28	2.2±0.1	213±17	117±8	39±9	96±19	347	60.1±3.4	76.7±1.8	90.7	286±38	25±6	1.950	74	209
R^6_{298}	**6**	298±19	216±14	1.2±0.1	104±8	70±7	20±8	34±7	201	64.0±2.7	74.4±2.2	90.8	197±21	27±14	1.366	145	209
R^6_{195}	**6**	195±15	120±10	0.8±0.1	89±8	53±6	4±3	36±7	107	53.3±3.9	69.3±3.5	97.1	159±16	12±5	1.162	115	209
R^6_{92}	**6**	92±10	55±5	0.4±0.0	43±3	30±3	2±2	13±3	48	50.4±5.4	66.0±4.5	96.4	157±11	21±11	2.377	558	83
Set 2 - UASB reactors operated with **similar COD_{Inf}**, but different HRT and OLR.																	
R^6_{816}	6	**816±45**	566±28	3.3±0.2	343±23	177±10	38±8	166±21	472	57.0±2.7	76.6±1.1	93.3	393±41	49±17	2.104	49	226
R^4_{770}	4	**770±38**	459±22	4.6±0.2	416±31	214±15	137±28	202±29	351	45.5±3.2	72.0±1.6	70.2	383±23	43±8	2.291	26	154
R^2_{787}	2	**787±31**	513±20	9.4±0.4	436±19	237±10	147±17	199±21	312	44.1±2.7	69.6±1.3	71.3	393±23	40±9	2.332	13	154
R^1_{716}	1	**716±42**	486±28	17.6±1.2	469±53	271±34	168±40	197±44	n.d.	36.6±5.3	63.1±4.6	65.4	368±82	111±33	1.933	6	83
Set 3 - UASB reactors operated with **similar OLR**, but different HRT and COD_{Inf}.																	
R^6_{816}	6	816±45	566±28	**3.3±0.2**	343±23	177±10	38±8	166±21	472	57.0±2.7	76.6±1.1	93.3	393±41	49±17	2.104	49	226
R^4_{558}	4	558±31	383±19	**3.3±0.2**	263±24	144±11	89±9	119±21	301	52.6±3.8	74.1±1.6	76.7	311±20	30±8	2.231	47	154
R^2_{352}	2	352±18	235±13	**4.2±0.2**	201±16	124±7	79±12	77±13	148	42.1±4.6	64.3±2.0	66.3	222±13	28±9	1.866	31	154
R^1_{136}	1	136±18	n.d.	**3.3±0.4**	110±16	61±7	n.d.	49±14	n.d.	13.7±13.3	52.0±5.6	n.d.	180±17	36±18	0.942	26	83

HRT = Hydraulic Retention Time (h); COD_{Inf}^{Tot} = Total Influent COD (mg/L); COD_{Inf}^{SS} = Influent suspended solids in term of COD (mg/L); OLR = Organic Loading Rate (kgCOD/m^3.day); COD_{Eff}^{Tot} = Total Effluent COD (mg/L); COD_{Eff}^{Set} = Settled Effluent COD (mg/L); COD_{Eff}^{SS} = Effluent suspended solids in term of COD (mg/L); COD_{Ef}^{X} = Excess sludge in term of COD (mg/L); COD_{CH4} = Methane production in terms of COD (mg/L);E_{Tot} = See Equation 2.1 (%); $E_{Set.}$ = See Equation 2.2 (%); E_{SS}^{Set}. = See Equation 2.3 (%); Alk_{Eff} = Effluent Total Alkalinity (mgCaCO$_3$/L); VFA_{Eff} = Effluent Total Volatile Fatty Acids (mg/L); M_X = Mass of volatile solids in the reactors (kgVS); SRT = Sludge Retention Time (days); Time = Total time of operation (days). ± values are Confidence Intervals (α=0.05). Reactor R^6_{816} is repeated to create the three sets above.

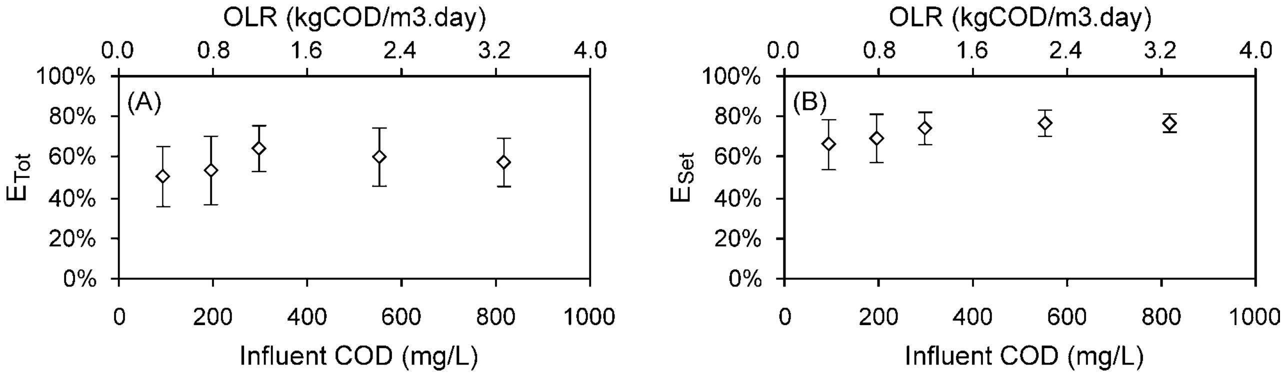

Figure 2.2 – Effect of Influent COD concentration on the reactor COD removal efficiency. (**A**) Total COD removal efficiency (E_{Tot}).(**B**) Efficiency based on settled-effluent COD (E_{Set}). Error bars represent Standard Deviation.

Assuming that the effluent SS is the non-settleable suspended COD fraction in the effluent, a slight decrease in the SS removal efficiency E_{SS}^{Set} occurred at increased influent COD (Figure 2.3). The data shows that the SS efficiencies E_{SS}^{Tot} also decrease when the reactors are operated with higher influent COD.

The results of E_{SS}^{Set} are opposite to what was expected because, according to Miron, 1997, the entrapment capacity would increase at high influent SS concentrations. Perhaps this author found different results because he used primary sludge to increase the influent concentration. Primary sludge is mainly comprised of well settleable suspended solids, which could have improved the removal performance at higher influent SS concentration. Nonetheless, the high E_{SS}^{Set} obtained under all imposed conditions, especially in reactor R^6_{195}, was the main cause of such high total COD removal efficiency at very low influent concentrations.

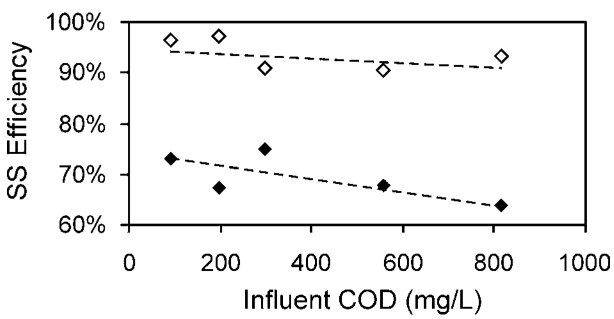

Figure 2.3 – Effect of Influent COD concentration on the reactor SS removal efficiency. (◆) SS removal efficiency based on total effluent SS - E_{SS}^{Tot}; (◇) SS removal efficiency based on settled effluent SS - E_{SS}^{Set}.

According to Kato (1994), the capacity of the UASB reactors for treating very low strength wastewaters can be explained by means of the half saturation value, k_s, of the Monod model. All reactors operated with HRT of 6 hours contained flocculent sludge, which has a low apparent k_s and thus a high affinity and capacity to treat sewage with a low substrate concentration (Lettinga *et al.*, 2000).

The Specific Methanogenic Activity (SMA) slightly increased with decreasing influent concentrations, viz. from 0.18kgCOD/kgVS.day at 30^{o}C for the reactor operated with influent COD of 816mg/L (reactor R^6_{816}) to 0.23 and 0.22kgCOD/kgVS.day for reactors operated with COD_{Inf} of 195 and 92mgCOD/L respectively (reactors R^6_{195} and R^6_{92}). However, total and settled COD removal efficiencies and methanisation decreased with diminishing COD_{Inf}. Moreover, at lowered COD_{Inf}, the reactors resulted in a decreased dissolved COD removal efficiency (E_{Dis}) and a decreased $VFA_{Eff}/COD_{Eff}^{Dis}$ ratio. This may indicate that at low concentrations (down to 200mgCOD/L), the acidification was the limiting step, which is in agreement with the observations of Kato, 1994. Figure 2.4 depicts the results of E_{Dis} and the calculated values for hydrolysis (H_{Tot}), acidogenesis (A_{Tot}) and methanogenesis (M_{Tot}), based on Equations 2.11, 2.12 and 2.13 respectively. The values of H_{Tot}, A_{Tot}, and M_{Tot} for the reactor operated with COD_{Inf} of 92mgCOD/L show that the methanogenesis is the limiting step in this case, which is probably due to errors in measurements of very low COD concentration and/or very low gas production.

$$H_{Tot} = \left(COD_{CH4} + COD_{Eff}^{Dis}\right) / COD_{Inf}^{Tot} \qquad \text{(Eq. 2.11)}$$

$$A_{Tot} = \left(COD_{CH4} + COD_{Eff}^{VFA}\right) / COD_{Inf}^{Tot} \qquad \text{(Eq. 2.12)}$$

$$M_{Tot} = COD_{CH4} / COD_{Inf}^{Tot} \qquad \text{(Eq. 2.13)}$$

Where: COD_{CH4} is methane gas production in terms of COD concentration; COD_{Eff}^{VFA} is the total VFA in the effluent in terms of COD concentration. All COD concentrations are expressed in mg/L.

As mentioned previously, the effect of influent concentration on the sludge retention time (SRT) was assessed using the methodology developed by Cavalcanti (2003) (Equation 2.5), which is the ratio between the volatile sludge mass in the reactor and the daily sludge production calculated from the amount of settleable VSS in the effluent. It is quite obvious that the SRT will increase with decreased influent concentration.

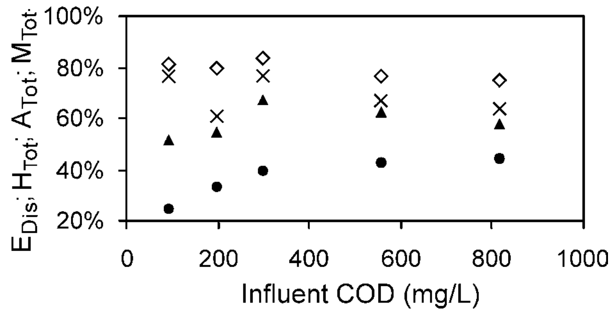

Figure 2.4 – Effect of Influent COD concentration on E_{Dis} - dissolved COD removal efficiency (●), H_{Tot} - Hydrolysis (◇), A_{Tot} - Acidogenesis (X) and M_{Tot} - Methanogenesis (▲). All anaerobic steps are based on total influent COD.

Another method for the calculation of the SRT was developed by Zeeman and Lettinga (1999) (Equation 2.14). Their method is based on the hydrolysis of the entrapped suspended solids (Equation 2.15), rather than sludge production. Both approaches actually lead to similar conclusions if one considers that the sludge production is the influent suspended solids which are removed, but not hydrolysed. Table 2.4 presents the parameters used for the model of Zeeman and Lettinga (1999), calculated using the experimental data obtained from reactors of Set 1. In Figure 2.5, the results of both models, Cavalcanti (2003) (Equation 2.5) and Zeeman and Lettinga (1999) (Equation 2.14), are depicted.

$$SRT = \left(HRT \times X_{VS}\right) / \left(COD_{Inf}^{Tot} \times SS \times E_{SS}^{Set} \times (1 - H_{SS}^{Rem})\right) \quad \text{(Eq. 2.14)}$$

$$H_{SS}^{Rem} = \left(COD_{CH4} + COD_{Eff}^{Dis} - COD_{Inf}^{Dis}\right) / \left(COD_{Inf}^{SS} - COD_{Eff}^{SS}\right) \quad \text{(Eq. 2.15)}$$

Where X_{VS} is the volatile solids sludge concentration in the reactor (gCOD/L); SS is the ratio $COD_{Inf}^{SS}/COD_{Inf}^{Tot}$; and H_{SS}^{Rem} is the fraction of the removed solids which is hydrolysed.

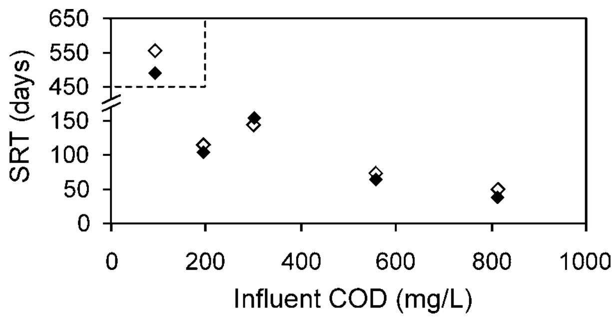

Figure 2.5 – Effect of Influent COD concentration on sludge retention time. SRT calculation using Equation 2.5 - Cavalcanti, 2003 (◇); Equation 2.14 - Zeeman and Lettinga, 1999 (◆).

Table 2.4 – Parameters for the models of Zeeman and Lettinga (1999), calculated based on values present in Table 2.3.

Reactor	HRT (h)	COD_{Inf}^{Tot} (gCOD/L)	SS	X_{VS} (gCOD/L)	E_{SS}^{Set}	H_{SS}^{Rem}
R^6_{816}	6	0.816	0.69	26.300	0.93	0.68
R^6_{555}	6	0.555	0.76	24.375	0.91	0.76
R^6_{298}	6	0.298	0.72	17.075	0.91	0.86
R^6_{195}	6	0.195	0.62	14.525	0.97	0.69
R^6_{92}	6	0.092	0.60	29.713	0.96	0.72

Effluent and Efficiency Variability

The Coefficient of Variation (CV) was used to evaluate effluent and removal efficiency variability. In this work, only the settled effluent was considered, as the total effluent COD includes the excess sludge. Figure 2.6A shows the calculated values of CV of the effluent COD and of treatment efficiency. The effluent COD and removal efficiency fluctuation tend to increase at a lower influent COD.

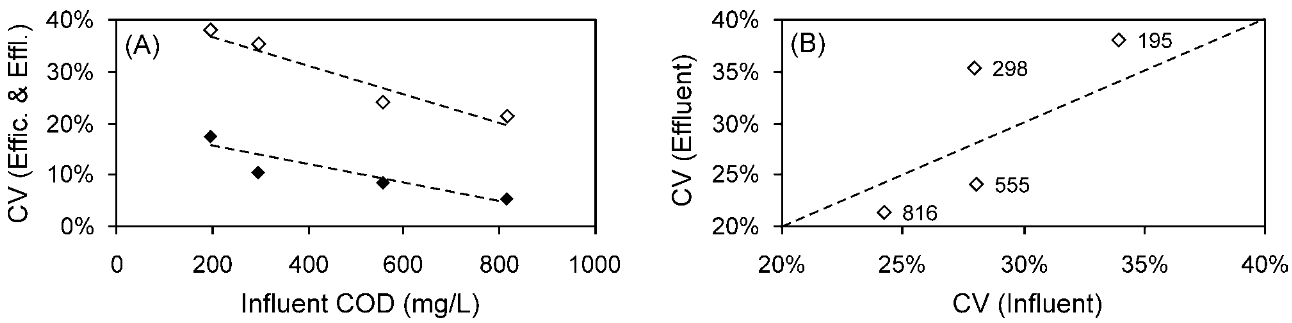

Figure 2.6 – (**A**) Effect of the influent COD on the fluctuation of effluent COD (◇) and treatment efficiency based on settled effluent COD (◆). (**B**) Effect of the influent variability on the effluent variability. Values inside graph B represent COD_{Inf}.

The influent COD fluctuation seems to be the main cause of the effluent variation because the effluent fluctuation increased as the influent fluctuation increased. However, this cannot be the only reason, as reactors which were operated at lower influent concentration gave an effluent with higher fluctuations than the influent (see points above the 45-degrees line in Figure 2.6B). It is possible that at a low COD concentration, the variation increased due to a higher analytical error. However, it is also possible that the variability of the biological process caused an additional fluctuation, as reported by Weber and Juanico (1990).

pH Stability

The operational stability of the UASB reactors was evaluated in terms of bicarbonate alkalinity, pH, total VFA concentration, VFA/bicarbonate alkalinity ratio and buffer capacity (results of bicarbonate alkalinity and buffer capacity are not shown). The VFA/bicarbonate alkalinity ratio was suggested by Behling *et al.* (1997), Fongastitkul *et al.* (1994), and Ripley *et al.* (1986), as a good indicator of the state of the reactor. According to these researchers, a value greater than 0.4 for this ratio might indicate that the anaerobic digester becomes unstable. The buffer capacity was assessed based on the methodology presented by van Haandel and Lettinga (1994), and van Haandel (1994).

The VFA concentration in the effluent of all reactors of Set 1 was low (less than 1mmol/L), and the total alkalinity and buffer capacity was relatively high. Accordingly, the VFA/bicarbonate alkalinity ratio was always less than 0.3. The pH remained in the range of 6.9 to 7.7 throughout the duration of the experimental period, so that there was no danger of reactor instability.

2.3.2. The Effect of the Hydraulic Retention Time on Reactor Performance

Reactor Efficiency

The efficiency of reactors operated with a different HRT and OLR (Set 2) and with similar influent CODs, is presented in Figure 2.7. The results show that with an HRT between 1 and 6 hours (V_{up} within the range of 0.64 to 3.80m/h) the efficiencies increased with longer HRT (or lower V_{up}). This is similar to the results found by van Haandel and Lettinga (1994), i.e. a decrease when V_{up} increases. However, these authors foresee a much sharper decrease of the COD removal efficiency at a shorter HRT. For shorter hydraulic retention times, a sharp decrease is likely to occur due to the increased sludge washout as well as the limited contact time for the physical and biological processes.

The data indicates that there is a trend for COD removal efficiency based on settled effluent to become constant for HRT longer than 4 hours (around 77%). This is because the SS removal efficiency was higher than 90%. Moreover, methanisation of the removed COD was 74% for the reactor operated with an HRT of 6 hours. This means that COD removal efficiency and methanisation can hardly be improved by an increase in HRT, as they are already very close to the maximum value (the biodegradability of the influent was around 77% - results not shown). What was exposed here is in agreement with results of Vieira and Garcia Jr. (1992). The latter authors found that within an HRT range of 5 to 15 hours, barely any improvement occurred in the reactor's performance, and the COD removal efficiency maintained a value of around 60%. The lower COD removal efficiency may be attributed to a high fraction of industrial wastewater from São Paulo (a large city in Brazil) in the municipal sewage used by the last authors.

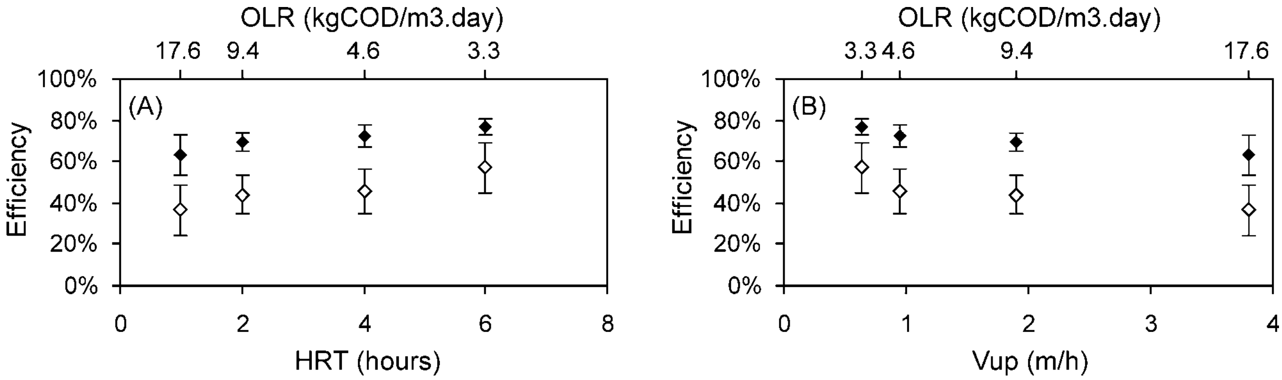

Figure 2.7 – Effect of HRT (**A**) and upflow velocity (**B**) on the reactor COD removal efficiency. (◇) Efficiency based on total effluent COD; (◆) Efficiency based on settled effluent COD. Error bars represent Standard Deviation.

Reactors R^4_{770}, R^2_{787} and R^1_{716} (operated with OLRs of 4.6, 9.4, and 17.6 kgCOD/m3.day respectively) showed very similar excess sludge washout (expressed in terms of COD), viz. around 200mgCOD/L, while for reactor R^6_{816} (operated with OLR=3.3kgCOD/m3.day) this value amounted to 166mgCOD/L. The total effluent SS concentration (as COD) increased considerably at an HRT lower than 6h (Figure 2.8A), and accordingly the SS removal efficiency decreased (Figure 2.8B). This is an indication that at a lower HRT, the hydrolysis step could not proceed properly, as shown in Figure 2.9. The analysis of variance shows that there is no difference (α=0.05) between the results of effluent SS of the reactors operated with HRT of 2 and 4 hours, which is an indication that the SS removal efficiency of these reactors did not differ significantly. This is in agreement with Ligero *et al*. (2001), who operated a hydrolytic upflow sludge bed reactor with an HRT within the range of 2.2 – 4.4 hours, and found SS removal efficiencies around 60% for all values of HRT. The high values of standard deviation for reactor R^1_{716} are due to very few results of SS obtained during the span of operation (5 determinations).

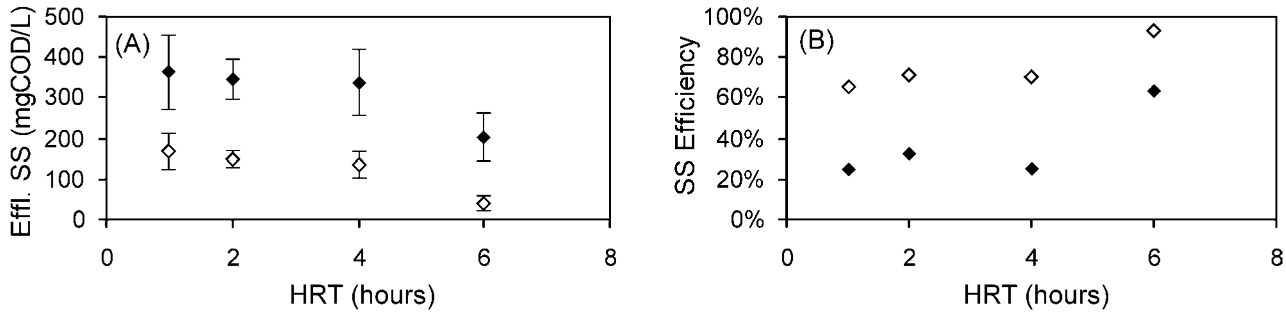

Figure 2.8 – Effect of HRT on the effluent suspended solids. (**A**) Total effluent SS (◆) and settled effluent SS (◇); (**B**) SS removal efficiency based on total effluent SS - E_{SS}^{Tot} (◆) and SS removal efficiency based on settled effluent SS - E_{SS}^{Set} (◇). Error bars represent Standard Deviation.

Domestic wastewater contains significant amounts of fats and suspended solids, both of which are detrimental to the granulation process (Souza, 1986). Nevertheless, the presence of granular sludge was observed in the reactors operated with V_{up} of 1.9 and 3.8 m/h (HRT of 2 and 1h respectively). This phenomenon is expected at high V_{up}, as a result of the selective retention of a highly settleable sludge (discussed in Chapter 4). This is an indication that the "selection pressure" can be less dependent on wastewater composition and strength (Foresti, 2002; and Barbosa and Sant'Anna Jr., 1989). However, the development of granules does not mean that the reactors become more efficient for the treatment of domestic sewage (Kalogo and Verstraete, 1999), because flocculent sludge is more effective in the entrapment of the suspended solids than granular sludge (Mulia, 2002).

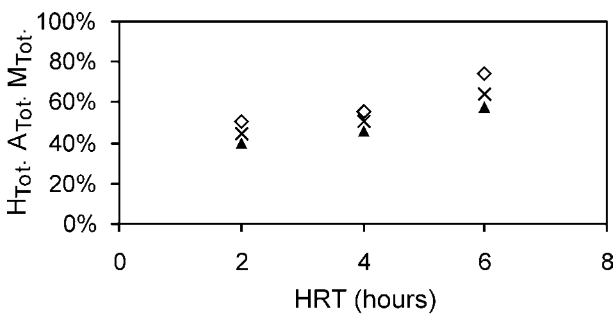

Figure 2.9 – Effect of HRT on H_{Tot} - Hydrolysis (◇), A_{Tot} - Acidogenesis (X) and M_{Tot} - Methanogenesis (▲). All anaerobic steps are based on total influent COD.

The effect of the HRT on the SRT was assessed using the same methodology presented in Section 2.3.1. Under the conditions applied to the reactors operated during this research, SRT increases when HRT increases. Table 2.5 presents the parameters used for the model of Zeeman and Lettinga (1999) using the experimental data obtained from reactors of Set 2. Actually, the two models resulted in similar values for SRT (Figure 2.10), as they only differ on the approach for the assessment of the sludge production. Cavalcanti (2003) used the difference between the total effluent COD and the settled effluent COD to obtain the excess sludge. Zeeman and Lettinga (1999) rather used the data of CH_4 production (as COD) and dissolved influent and effluent COD to assess the sludge production, through the hydrolysis of the entrapped suspended solids (Equation 2.16).

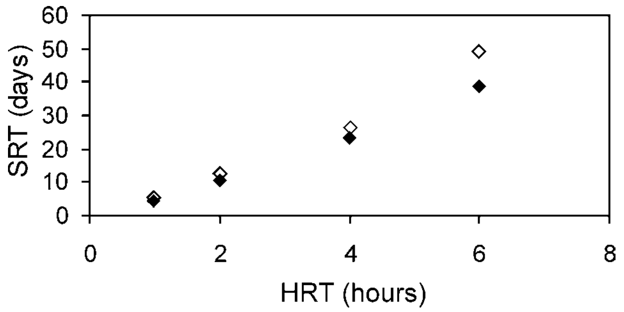

Figure 2.10 – Effect of HRT on sludge retention time. SRT calculation using Equation 2.5 - Cavalcanti, 2003 (◇); Equation 2.14 - Zeeman and Lettinga, 1999, (◆).

Table 2.5 – Parameters for the models of Zeeman and Lettinga, 1999, and Cavalcanti, 2003, calculated based on values present in Table 2.3.

Reactor	HRT (h)	COD_{Inf}^{Tot} (gCOD/L)	SS	X_{VS} (gCOD/L)	E_{SS}^{Set}	H_{SS}^{Rem}
R^6_{816}	6	0.816	0.69	26.300	0.93	0.68
R^4_{770}	4	0.770	0.60	28.638	0.70	0.36
R^2_{787}	2	0.787	0.65	29.150	0.71	0.34
R^1_{716}	1	0.716	0.68	24.163	0.65	0.36

Effluent and Efficiency Variability

The influence of hydraulic retention time on the fluctuation of the reactor performance is depicted in Figure 2.11. Reactor R^6_{816} (HRT=6h) had the highest influent fluctuation (CV=24.2%), but its COD removal efficiency did not vary significantly (Figure 2.11A). In contrast, reactor R^1_{716} operated with an HRT of 1 hour and with an influent CV of only 18.2%, resulted in an effluent with the highest fluctuation. The probable explanation is the higher equalisation capacity of the reactor at a longer HRT, which can smooth the influent fluctuation (Metcalf & Eddy, 1991). As illustrated in Figure 2.11B, the influent variation has a strong effect on the effluent fluctuation.

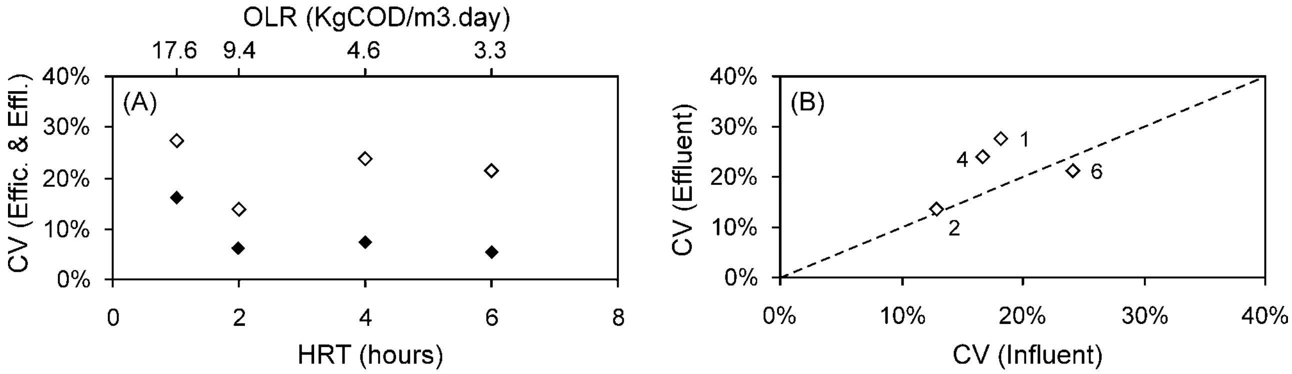

Figure 2.11 – (**A**) Effect of HRT on the fluctuation of effluent COD (◇) and treatment efficiency based on settled effluent COD (◆). (**B**) Effect of the influent variability on the effluent variability. Values inside graph B represent HRT.

pH Stability

The VFA concentration in the effluent of reactors R^{6}_{816}, R^{4}_{770}, and R^{2}_{787} was low (less than 1mmol/L), and the pH during the whole experimental period remained in the range of 7.0 to 8.2. Buffer capacity was favourable in all these reactors, and the VFA/alkalinity ratio was lower than 0.3.

Reactor R^{1}_{716} was operated under extreme conditions, with an HRT of 1 hour and OLR of 17.6kgCOD/m^3.day. However, despite the fact that pH values were still in their optimum range for the anaerobic process, (varying from 6.6 to 7.1), effluent VFA concentration was high (average of 111mg/L) and the VFA/bicarbonate alkalinity ratio appeared to be at a risky level (0.5). In contrast, buffer capacity was very high due to the high influent alkalinity. In addition to problems with high VFA and VFA/bicarbonate alkalinity ratio, reactor R^{1}_{716} presented frequent events of sludge washout and scum formation.

2.3.3. The Effect of the Organic Loading Rate on Reactor Performance

Reactor Efficiency

The OLR applied to the reactor depends on the influent concentration, flow rate and reactor volume, and therefore, also on the imposed hydraulic retention time (Equation 2.16). The effect of the applied OLR itself on the reactors efficiency is not clear, since this parameter is a function of others that have contradictory effects on the reactor performance, i.e. to increase the influent concentration (and hence OLR) up to a certain limit leads to an increase in removal efficiency based on total and settled effluent (see Section 2.3.1), and increasing the flow rate (and consequentially OLR) induces a decrease in efficiency (see Section 2.3.2). Thus, in order to characterise the UASB's performance in treating sewage, the OLR has to be analysed in combination with HRT and/or COD_{Inf}, in agreement with Mahmoud (2002). Reactors of Set 3 were operated with the approximate same applied OLR (different sets of HRT and COD_{Inf}), but resulted in completely different levels of efficiency (see Figure 2.12 A and B).

$$OLR = (COD_{Inf}^{Tot} \times Q)/V = COD_{Inf}^{Tot}/HRT \qquad \text{(Eq. 2.16)}$$

Where ORL is the organic loading rate in $kgCOD/m^3.day$. COD_{Inf}^{Tot} is the total influent concentration (kgCOD/L); Q is the flow rate in L/day; V is the reactor volume (m^3), and HRT is the hydraulic retention time in days.

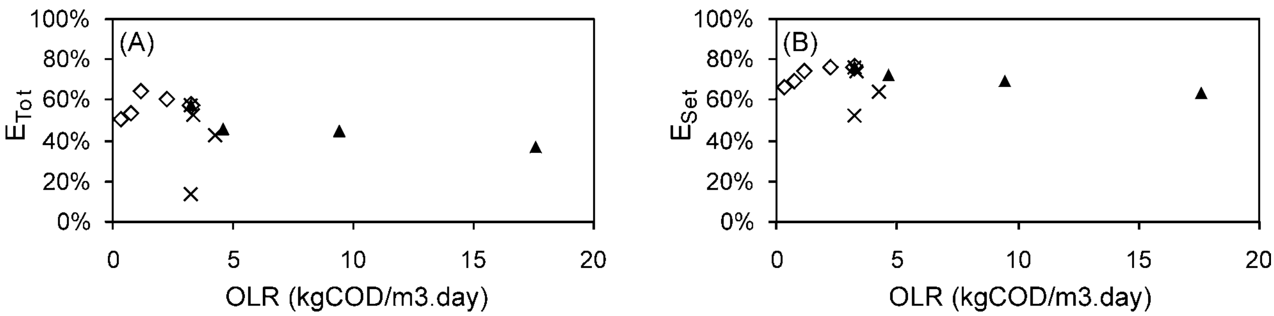

Figure 2.12 – Effect of applied OLR on the reactor COD removal efficiency. (**A**) Total COD removal efficiency - E_{Tot}. (**B**) Efficiency based on settled effluent COD - E_{Set}.
◇ - Set 1: HRT=6h and COD_{Inf} from 92 to 816mg/L. ▲ - Set 2: HRT from 1 to 6h and COD_{Inf}~800mg/L. X – Set 3: HRT from 1 to 6h and COD_{Inf} from 136 to 816mg/L.

An increase in the OLR causes a decrease in SS removal efficiency (Figure 2.13A). This is possibly due to at least one of the following reasons: If the strengthening of the OLR is due to dissolved COD, the turbulence caused by gas production can cause SS washout. If the OLR augmentation is due to the decrease of HRT, sludge washout and short contact time for the physical and biological process are the cause for the lower SS removal efficiency. However, when the OLR increases as a result of a raise in suspended solids, the SS entrapment capacity of the reactor become an important factor for the increased reactor efficiency. Miron (1997) found that the COD removal efficiency increases when the OLR is raised, which was accomplished by increasing the influent concentration using primary sludge (high SS fraction). These observations were actually opposite to the findings in our research, i.e. a slight decrease in SS removal efficiency at increased influent SS concentration, as can be seen in Figure 2.13B. As mentioned before, Miron (1997) used primary sludge in his research, which could have overestimated the SS removal efficiency of his reactor due to the high settleability of such suspended solids. Mulia (2002) operated lab-scale UASB reactors, which were inoculated with flocculent sludge and fed with municipal sewage, and found no clear correlation between OLR and SS removal efficiency. The problem is, if one of the parameters, either HRT or COD_{Inf}, changes the other should change to maintain the same OLR, e.g. if the COD_{Inf} is reduced one must increase the flow rate (decrease the HRT) to maintain the same OLR. Thus, it is consequently difficult to come to a clear conclusion about the effect of OLR on the UASB performance.

In UASB reactors treating sewage, the SRT is higher at lower organic loading rates. Generally, one may affirm that at a short SRT, the methanogenesis becomes the limiting step of the stabilisation process, as the slow-growing methanogenic bacteria washout at such conditions. However, the limiting step cannot be assessed based on solely SRT. This is because decreasing SRT by lowering the HRT (increasing the V_{up}) leads to a higher concentration of active methanogenic biomass, which was grown under the high volatile fatty acids loading rate (VFA was present in the raw sewage at a concentration of around 180mg/L as acetic acid). This contradictory phenomenon, i.e. short SRT and high SMA, is explained in Chapter 3.

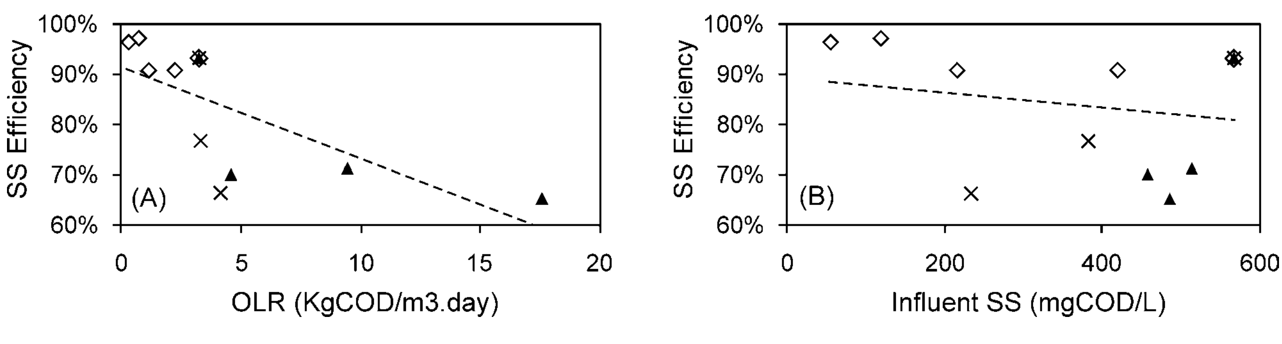

Figure 2.13 – Effect of OLR (**A**) and influent SS concentration (**B**) on the suspended solids removal efficiency. ◇ - Set 1: HRT=6h and COD_{Inf} from 92 to 816mg/L. ▲ - Set 2: HRT from 1 to 6h and COD_{Inf}~800mg/L. X – Set 3: HRT from 1 to 6h and COD_{Inf} from 136 to 816mg/L.

Effluent and Efficiency Variability

The results of Coefficient of Variation (CV) from data obtained during the span of the research (Sets 1, 2 and 3) are presented in Figure 2.14. In general, effluent fluctuation tends to increase as the OLR decreases (see Figure 2.14A). It seems that influent variation has more influence on effluent fluctuation than any other parameter, but in most cases higher values of CV were found for effluent rather than influent. This is an indication that some intrinsic variations are built up in the reactors (Figure 2.14B).

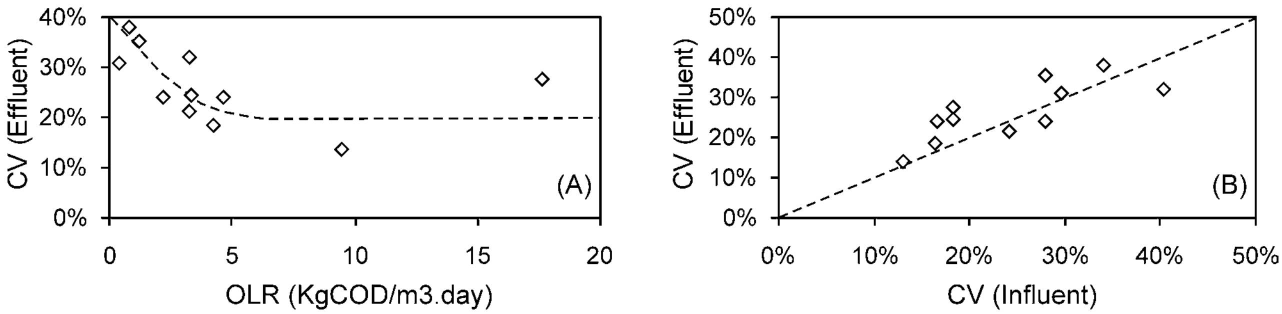

Figure 2.14 – (**A**) Effect of OLR on the fluctuation of settled effluent. (**B**) Effect of the influent variability on the settled effluent variability.

For reactor R^1_{136}, which was operated under extreme conditions (HRT of 1 hour and COD_{Inf} of 92 mg/L), a CV of 280% for total COD removal efficiency was found, reflecting frequent events of sludge washout. Fluctuations on the efficiency of the reactors tended to increase at lower influent concentration (Section 2.3.1), but decreased at a higher HRT (Section 2.3.2). As OLR is directly proportional to the COD_{Inf} and inversely proportional to HRT, a high value of CV for COD removal efficiency would be expected under extreme operational conditions, such as those found in reactor R^1_{136}.

pH Stability

With regards to the stability of process performance, the pH values of reactors R^6_{816}, R^4_{558} and R^2_{352} were always between 7.0 and 8.1, the total volatile fatty acids concentrations were low (see Table 2.3), and the buffer capacity was consequently very high. However, under the conditions of 1 hour of hydraulic retention time and at very low influent concentration (136mgCOD/L), such as those imposed to the R^1_{136}, reactor performance deteriorated. This worsening occurred despite the fact that the OLR was not very high (3.3kgCOD/m^3.day). Moreover, the dilute influent decreased the supply of alkalinity, which lowered the buffer capacity and raised the VFA/Alkalinity ratio.

2.4. FINAL DISCUSSION

In tropical countries, where sewage temperatures are > 20^{o}C, UASB reactors can treat municipal wastewater with a concentration as low as 200mg/L, attaining COD removal efficiency up to 69% (based on settled effluent), as long as a reasonable HRT is applied, e.g. 6 hours. The maximum COD removal efficiency (around 60% for total effluent and 77% for settled effluent) can be achieved at influent concentrations exceeding 300mgCOD/L and at HRT of 6 hours. However, for the treatment of influents with a COD concentration below 200mg/L, the reactor becames less efficient and unstable with regards to effluent variability.

The SS removal efficiency slightly increases as the influent concentration decreases. This is possibly due to the very low gas production which causes less turbulence in the sludge bed, and consequently improves the filterability (or the entrapment capacity) of the sludge. In contrast, the dissolved COD removal efficiency decreases drastically at lowered influent concentrations because the acidification becomes the limiting step. This may be due to mass transfer limitations at low substrate concentrations. In fact, the relatively high concentration of dissolved COD in the effluent is a reflection of the reduced performance of the reactor at low influent concentrations.

The reactors operated with HRT of 6 hours and influent concentration of 816mgCOD/L resulted in SS removal efficiency (E_{SS}^{Set}) of 93.3% and methanisation of the removed COD of 73.8%. This means that the efficiency can hardly be improved, as E_{SS}^{Set} was already very high and the methanisation was almost the same as the biodegradability of the influent (77%). Thus, it seems useless to operate UASB reactors in tropical countries with an HRT exceeding 6 hours.

Hydraulic retention times below 6 hours tend to deteriorate the performance of UASB reactors. The removal efficiencies for both COD and SS significantly decrease when the reactor is operated at an HRT of 4 hours. A further decrease in HRT (to 2 hours) did not cause appreciable changes in removal efficiencies of COD or SS, nor cause an increase on the effluent variability. However, a lower HRT (1 hour) is too severe for the UASB reactors, and it is difficult for the entrapment of suspended solids to occur under such conditions. Moreover, effluent VFA concentration increased at the extreme condition of HRT of 1 hour and high influent concentration (reactor R^1_{716}). Reactors R^1_{716} and R^1_{136} (HRT=1h) were not operated for a long period of time (83 days). Therefore, doubts still remain as to whether they were at steady state, or they would finally fail if they had been operated for a longer period.

The results obtained from reactors operated with short HRT can be used for an evaluation of a two-step process for sewage treatment, such as the HUSB (Hydrolysis Upflow Sludge Bed reactor) + UASB, supported by Wang (1994). This system was meant to treat sewage at temperatures below 20°C, as in this condition, the hydrolysis proceeds slowly and SS accumulate, decreasing the SRT and preventing the development of the methanogens in the first step. However, the results of this research show that at a temperature of around 27°C, methanogenesis was not limited at HRT as low as 2 hours and upflow velocity of 1.9m/h (SRT of 13 days). This is an indication that the application of a two-step system, as proposed by Wang (1994), is not suitable for tropical countries with sewage concentration in the range of 300 – 800mgCOD/L, as methanogenesis will always occur in the first step.

In the present study, a two-step system UASB-Secondary Settler was simulated by determining the settled effluent. It is in fact the opposite of which was proposed by Wang (1994), as the SS removal occurs in the second step. For the operational mode imposed during our research, i.e. reactor operated without intentional sludge discharge, this fictitious secondary settler was fundamental for the improvement of effluent quality increasing the treatment efficiency.

The effect of the OLR is quite difficult to evaluate, as it is a function of two other parameters (COD_{Inf} and flow rate or HRT), which have a contradictory effect on the UASB performance and stability. At first, one can affirm that increasing the OLR will lead to a decreased efficiency in the removal of suspended solids. But for a given OLR, the reactor performance would be at its best with a long HRT and high influent COD concentration (up to a certain limit). The opposite can cause a remarkable decrease on the UASB performance, and a dramatic increase on the effluent variability, which is illustrated in Figure 2.15.

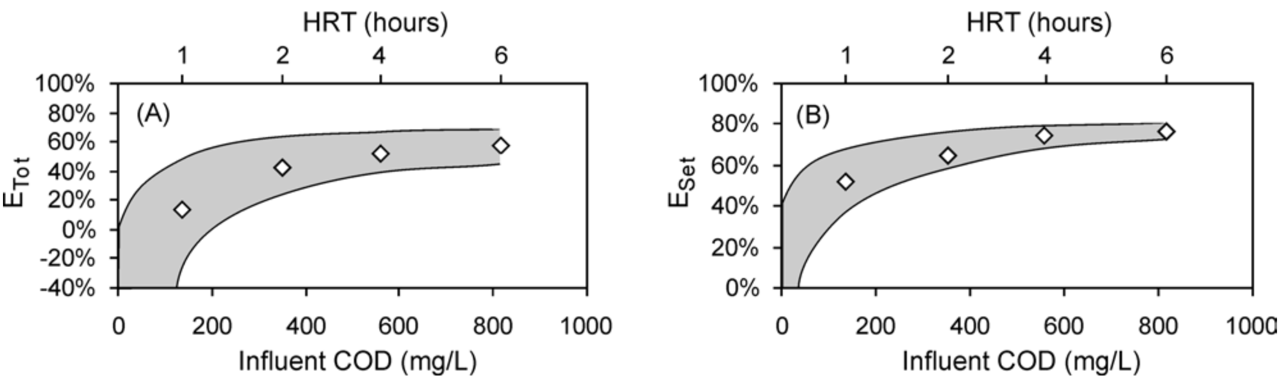

Figure 2.15 – Effect of HRT and COD_{Inf} on COD removal efficiency: (**A**) based on total effluent – $E_{Tot;}$ (**B**) based on settled effluent - E_{Set}. Results obtained form reactors of Set 3, operated with the same OLR (approximately 3.3kgCOD/m^3.day), but with different HRTs and COD_{Inf}. The grey zone represent the efficiency range based on standard deviation.

The experiments show that for a particular HRT, the UASB reactors maintain approximately the same COD removal efficiency irrespective of the influent COD concentration (at least in the range of 300 – 800mgCOD/L). When a particular organic load from a municipality is to be treated, the COD concentration may increase when dilution with other waters (rain, infiltration) is avoided. When this happens, the flow rate decreases and the reactor can be designed with a smaller volume without deteriorating the performance.

When applying the Analysis of Variance on the performance of the various reactors, it appears that there is no significant difference between either reactors R^4_{770} and R^4_{558} (HRT of 4 hours), or reactors R^2_{787} and R^2_{352} (HRT of 2 hours). This indicates that the HRT has a stronger effect on the UASB performance and stability than influent COD concentration.

2.5. CONCLUSIONS

(i) COD removal efficiency: Decreasing the influent concentration and/or decreasing the HRT leads to decreased efficiencies. The maximum COD removal efficiency is achieved with an HRT of longer than 4 hours, and an influent concentration higher than 300mgCOD/L.

(ii) Effluent variability: Effluent variability is highly dependent on the influent variability. The fluctuations increase with decreased HRT due to a decreased reactor equalisation capacity. The effluent variability also increases with lowered influent concentrations because analytical errors become more noticeable.

(iii) Stability during steady state: UASB reactors treating municipal wastewater in tropical countries are extremely stable with regards to pH and buffer capacity, indicating that it is very difficult for an operational or environmental situation to arise that causes acidification. The studied UASB reactor only showed some evidence of pH instability at very extreme operational conditions, such as an operation with an HRT shorter than 2 hours and/or influent concentration lower than 200mgCOD/L. This kind of reactor might possibly never achieve the so-called pseudo steady state condition under such extreme circumstances.

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3

THE EFFECT OF OPERATIONAL CONDITIONS ON THE SLUDGE SPECIFIC METHANOGENIC ACTIVITY AND SLUDGE BIODEGRADABILITY

The Specific Methanogenic Activity (SMA) and sludge biodegradability of an anaerobic sludge depends on various operational and environmental conditions imposed to the anaerobic reactor. However, the effects of hydraulic retention time (HRT) and influent COD (chemical oxygen demand) concentration on these two parameters need to be elucidated. In this work, different sludge samples obtained from 8 pilot-scale Upflow Anaerobic Sludge Blanket (UASB) reactors were tested. The reactors were fed with municipal wastewater, and operated with different sets of HRT (2, 4 and 6 hours) and influent concentrations (approximately 200, 300, 350, 550, and 800 mgCOD/L). When a "steady state" had been established, sludge samples were withdrawn from taps located at four different heights of each reactor to assemble composite samples, which were then used for the tests. The results show that at a lower HRT, and consequently a higher upflow velocity, sludge with relatively higher SMA develops. The effect of influent COD concentration (COD_{Inf}) on the SMA is still not clear. A slight trend of declining SMA at increasing COD_{Inf} was found for reactors operated at longer HRTs, but further experiments are necessary for more definitive conclusions. The sludge from reactors operated at long HRTs and with low COD_{Inf} resulted in low biodegradability. Results also show that it is worthless to design an UASB reactor with a longer HRT to cope with organic shock loads.

3.1. INTRODUCTION

3.1.1. Specific Methanogenic Activity

The Specific Methanogenic Activity (SMA) test allows the determination of the maximum methane production rate of an anaerobic sludge under controlled environmental conditions (Silveira and Monteggia, 2000). The results of SMA tests for a given sludge can vary depending on several parameters, such as medium composition and microbial culture (Kettunen and Rintala, 1997), ratio between the initial substrate concentration and sludge concentration in the batch test (Moreno *et al.*, 1999), inhibition due to oxygen (Stephenson *et al.*, 1999; and Kato *et al.*, 1997), temperature, shaking conditions, sampling conditions (single or composite samples, and sampling position), as well as the methodology for measuring the methane production (headspace methods, liquid displacement method, pressure monitoring methods, etc.). The standardisation of the SMA test procedure is actually still under development. Despite the different methods of estimating the SMA, the methane production rates of various sludges can be compared using one of the aforementioned methods.

Sludge activity depends on various operational parameters including hydraulic retention time (HRT), upflow velocity (V_{up}), organic loading rate (OLR), influent COD (chemical oxygen demand) concentration (COD_{Inf}) and characteristics, sludge retention time (SRT), operational temperature, presence of inhibiting factors or xenobiotics compounds, and reactor configuration (Lettinga, 1995). However, the results obtained from the literature about the effect of HRT, V_{up}, and COD_{Inf} on SMA are contradictory.

Jawed and Tare (1996) investigated the performance of an Upflow Anaerobic Sludge Blanket (UASB) reactor fed with diluted molasses, and concluded that increasing the OLR by decreasing the HRT leads to a decreasing SMA. The same observation was made by Kalyuzhnyi *et al.* (1996), who operated a lab-scale UASB reactor fed with a mixture of glucose and acetate under different operational conditions and found that decreasing the HRT from 6.3 to 4 hours caused a decrease in the SMA. On the other hand, O'Flaherty *et al.* (1997), used upflow hybrid reactors fed with a solution of volatile fatty acid and alcohol to assess HRT and V_{up} effects on the SMA. He concluded that decreasing the HRT from 8 to 4 hours and raising the V_{up} from 0.01 to 0.5m/h would result in an increase of 200% in the SMA. This is in agreement with Guiot *et al.* (1992), who performed experiments in 4 anaerobic hybrid reactors fed with sucrose and nutrients, and concluded that increasing the V_{up} (from 0.9 up to 6.6 m/h) leads to increased SMA.

According to Jeison and Chamy (1999), and Kato *et al.* (1997), based on experiments in reactors treating dilute wastewater containing ethanol, the prevailing low substrate concentration in the sludge is the main reason for the relatively low SMA. This is similar to the findings of Alves *et al.*

(1998), who performed experiments with two anaerobic filters fed with skim milk. They found that increasing influent COD results in a higher sludge SMA. On the other hand, Jawed and Tare (1996), investigated the performance of an UASB reactor fed with diluted molasses and found that increasing the OLR by increasing the influent COD leads to a decreasing SMA.

Ghangrekar *et al.* (1996) operated lab-scale UASB reactors fed with sewage under different HRTs, V_{up}, and COD_{Inf}. They found that the sludge SMA did not follow any trend with respect to these parameters.

Regarding the discordant information available in the literature, it is clear that the effects of operational conditions (HRT, V_{up}, and COD_{Inf}) on the SMA still need to be clarified. This is important because the knowledge about the effect of these parameters on the SMA can provide insights about the capacity of the UASB reactors to withstand organic and hydraulic shock loads.

3.1.2. Sludge Biodegradability

Sludge biodegradability, or conversely sludge stability, is a parameter used to estimate the fraction of the organic material in the sludge that still can be biologically converted into methane and inert compounds. The sludge stability refers to the inert fraction, while the sludge biodegradability refers to the degradable fraction.

The effect of the operational conditions imposed to UASB reactors on the biodegradability of the sludge has been scarcely reported in literature. Moreover, as mentioned already by Mgana (2003), it is very difficult to compare the data obtained by the few researchers who had carried out studies on that field (Chaggu, 2004; Mgana, 2003; Mahmoud, 2002; Halalsheh, 2002; and van Haandel and Lettinga, 1994), as each of them had followed different experimental procedures (e.g. the use of nutrients and inoculum, and duration of the experiments).

The biodegradability of sludge has an inverse relationship with the SRT, i.e. the shorter the SRT the higher the biodegradability of the sludge. In an UASB reactor treating sewage, the SRT depends on the influent COD concentration (both suspended and dissolved fractions, as well as the biodegradability of the first mentioned fraction) and the imposed HRT. In Chapter 2, the SRT was assessed using the methodology developed by Cavalcanti (2003), which is the ratio between the volatile sludge mass in the reactor and the daily sludge production calculated from the amount of settleable volatile suspended solids (VSS) in the effluent. It is quite obvious that the SRT will increase with decreased influent concentration and/or increased HRT, as the suspended solids (SS) load will decrease. For that reason, the biodegradability of the sludge will decrease in these cases.

If the UASB reactor is operated under conditions of maximum sludge retention capacity, as in the case of the present research, the biodegradability of the sludge becomes an important issue. This is because the excess sludge is discharged together with the effluent and has to be removed (or accumulated) in a secondary unit, e.g. a settler, or a polishing pond as proposed by Cavalcanti (2003). In case the secondary unit is a settler, high biodegradable sludge can cause deterioration in the settler performance due to a high gas production rate. In addition, biodegradability is important in cases where intentional sludge wastage is applied, as this parameter directly affects the treatability (filterability and dewaterability) of the discharged sludge (Mahmoud, 2002).

3.1.3. Scope of this Chapter

In this chapter sludges obtained from different UASB reactors were tested to evaluate the effect of the influent COD concentration, hydraulic retention time, and upflow velocity on the sludge Specific Methanogenic Activity and Sludge Biodegradability. To achieve this goal, eight pilot-scale UASB reactors fed with municipal wastewater were operated until “steady state” conditions had been established, with different sets of hydraulic retention times and influent concentrations. Composite samples of sludge taken from each reactor were tested in terms of SMA and sludge biodegradability after 30 days at 30^{o}C.

3.2. MATERIAL AND METHODS

3.2.1. Experimental Set-Up

The experimental investigation was carried out utilising eight out of the 11 pilot-scale UASB reactors described in Chapter 2. Briefly, these reactors had a volume of 120 litres, and were fed with domestic sewage at a temperature of around 27^{o}C. The pilot-scale reactors operated in this work were denominated by $R^{HRT}{}_{COD}$, where the superscript index stands for the hydraulic retention time, and the subscript index stands for the total influent COD. Both are the averages during “steady state” conditions.

The main operational parameters related to this part of the research are presented in Table 3.1. When a “steady state” had been established, the sludge samples were withdrawn from taps located at four heights of the reactors (0.25, 1.00, 1.75 and 2.50 meters from the bottom) to assemble composite samples. Details about the “steady state” conditions are presented in Chapter 2.

It is important to note that all reactors were operated without recirculation, i.e. changing the HRT implies a change in V_{up}, since HRT=h/V_{up}, where “h” is the reactor height. Therefore, the evaluation of the effect of HRT on the SMA is also an evaluation of the effect of V_{up} for this research.

3.2.2. Specific Methanogenic Activity Tests

The SMA was determined following laboratory protocols from the Department of Environmental Technology of Wageningen University. The tests were carried out in 0.6 litre serum bottles sealed with rubber septum kept in place by a screw cap. Sludge in amounts of 2gTS and acetate in amount of 1.0gCOD were added to each bottle, then the liquid volume was completed to 0.4 litre (the final concentrations of sludge and acetate are 5gTS/L and 2.5gCOD/L respectively) with a solution comprised of distilled water, pH buffer, nutrients, trace elements and sodium acetate. Nutrients and trace elements, as described by Chaggu (2004), were added to the bottles to prevent deficiency during the test. The activity tests were performed at a temperature of 30±2^{o}C, and in shaking conditions (approximately 100rpm) to avoid diffusion limitation. The total volatile solids (VS) content of the sludge was determined prior to the SMA test to calculate the specific activity. Methane production was monitored daily during the test by using a NaOH solution (5%w/w) displacement system, a sort of Mariotte bottle. All experiments were performed in triplicate.

Table 3.1 – Operational parameters

Reactor	HRT (h)	Vup (m/h)	COD_{Inf}^{Tot} (mg/L)	COD_{Inf}^{SS} (mg/L)	COD_{Inf}^{Dis} (mg/L)	VFA_{Inf} (mgCOD/L)	OLR (KgCOD/m^3.day)
------ Set 1 - UASB reactors operated with the same HRT, but different COD_{Inf} and OLR. ------							
R^6_{816}	**6**	**0.64**	816±45	566	250	180	3.3
R^6_{555}	**6**	**0.64**	555±36	421	135	88	2.2
R^6_{298}	**6**	**0.64**	298±19	216	82	42	1.2
R^6_{195}	**6**	**0.64**	195±15	120	75	28	0.8
------ Set 2 - UASB reactors operated with similar COD_{Inf}, but different HRT and OLR. ------							
R^6_{816}	6	0.64	**816±45**	566	250	180	3.3
R^4_{770}	4	0.95	**770±38**	459	312	164	4.6
R^2_{787}	2	1.90	**787±31**	513	275	164	9.4
------ Set 3 - UASB reactors operated with similar OLR, but different HRT and COD_{Inf}. ------							
R^6_{816}	6	0.64	816±45	566	250	180	**3.3**
R^4_{558}	4	0.95	558±31	383	175	103	**4.2**
R^2_{352}	2	1.90	352±18	235	117	62	**3.4**

COD_{Inf}^{SS} and COD_{Inf}^{Dis} refer respectively to the suspended solids and dissolved fraction of the total influent COD. VFA_{Inf} refers to the influent volatile fatty acids (mgAc./L). ± values are Confidence Intervals (α=0.05). Reactor R^6_{816} is repeated to create the three sets above.

3.2.3. Sludge Biodegradability

The biodegradability tests were carried out utilising the same serum bottles used for the SMA tests. Sludge in amounts of 400mL was added to the bottle. No nutrients, substrate, nor buffer were added. The tests were performed at a temperature of 30±2°C, and in shaking conditions (approximately 100rpm). The total volatile solids content of the sludge was determined prior to the biodegradability test to calculate the fraction converted to methane. Methane production was monitored daily during the test by using a NaOH solution (5%w/w) displacement system, a sort of Mariotte bottle. All experiments lasted 30 days. The sludge anaerobic biodegradability and stability were calculated with Equations 3.1 and 3.2.

$$\text{Bio} = \left(\text{COD}_{\text{CH4}}^{30} \big/ \text{COD}_{\text{X}}^{0} \right) \times 100 \qquad \text{(Eq. 3.1)}$$

$$\text{Stab} = \left(1 - \left(\text{COD}_{\text{CH4}}^{30} \big/ \text{COD}_{\text{X}}^{0} \right) \right) \times 100 \qquad \text{(Eq. 3.2)}$$

Where: “Bio” is the Biodegradability of the sludge (%), “Stab” is the Stability of the sludge (%), COD^{30}_{CH4} is the total amount of methane produced at the end of the test (30 days) in terms of COD (g), and COD^{0}_{X} is the initial mass of sludge added to the serum bottles (g). COD^{30}_{CH4} was calculated based on the Henry’s law. COD^{0}_{X} was calculated based on the VS content of the sludge and assuming that 1g VS is equivalent to 1.5 gCOD.

3.3. RESULTS AND DISCUSSION

3.3.1. Specific Methanogenic Activity

The Effect of HRT and V_{up} on the SMA

Specific Methanogenic Activity was higher for sludges from reactors which were operated at shorter HRTs and higher V_{up} (see Set 2 in Figure 3.1). This phenomenon can be likely attributed to at least one of the following reasons:

(i) A selective retention of a sludge with higher SMA in reactors that were operated at higher upflow velocities (O'Flaherty *et al.*, 1997; and Lettinga, 1995). This mechanism indeed seems to be confirmed by the results obtained with reactor R^2_{787} (V_{up} of 1.90m/h), because at the termination of the experiment, this reactor contained a granular-type of sludge. This sludge also attained the highest SMA (0.59gCOD/gVS.day).

(ii) A high concentration of biomass which was grown under the high volatile fatty acids (VFA) loading rate. The substrate for methanogenic microorganisms was partially independent of the anaerobic food chain, because VFA was present in the influent at a concentration of around 180mg/L as acetic acid, which possibly improved the growth of this specific trophic group. Thus, the increased SMA at decreased HRT can be interpreted as a larger relative mass of methanogenic bacteria (Guiot *et al.*, 1992).

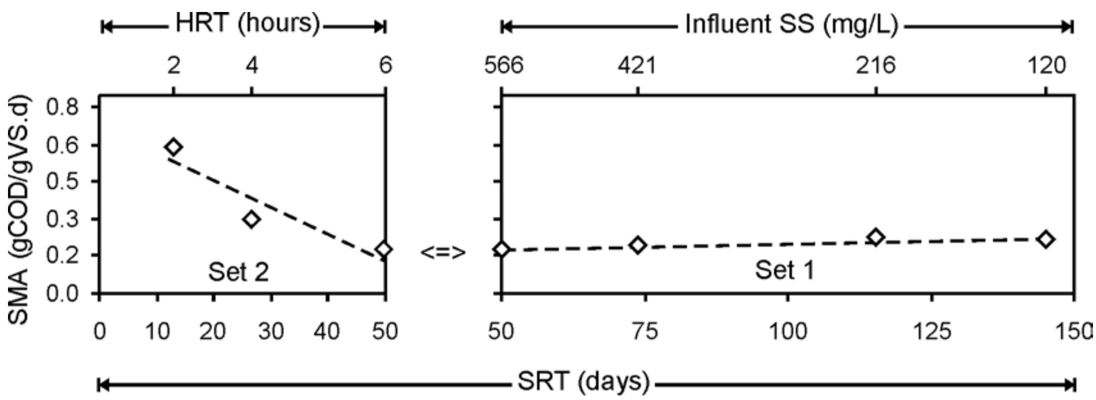

Figure 3.1 – Effect of SRT, HRT and influent SS concentration on the SMA.
Set 1: Reactors operated with different COD_{Inf}, but at the same HRT (6 hours).
Set 2: Reactors operated at different HRT, but approx. the same COD_{Inf} (~800mg/L).

According to Cavalcanti (2003), Mahmoud (2002) and Zeeman and Lettinga (1999), the longer the SRT, the better the sludge quality (in terms of methanogenic activity, stability, settleability and filterability), up to a certain limit. However, with regard to methanogenic activity, it seems to be true only if the sludge age is increased by decreased influent SS concentration (see Set 1 in Figure 3.1). Even so, this rise does not seem considerable compared with Set 2. During the treatment of domestic sewage, a short hydraulic retention time leads to short SRT and a high SMA, at least within the SRT range between 13 and 49 days (see Set 2 in Figure 3.1).

The Effect of COD_{Inf} on the SMA

The effect of the influent COD concentration on the SMA is not clear. It seems that SMA tends to decrease slightly when the COD_{Inf} increases, although merely for sludge obtained from the reactors operated with HRTs of 6 hours (see Figure 3.2). However, the opposite effect was found for reactors operated at HRT of 2 hours. It is possible that the influent concentration in the range of 200-800mgCOD/L barely affected the SMA, and the differences in sludge SMA perceived for reactors operated with the same HRT are in the error range for such tests (the values of the triplicate test differ in a range between of ±4 and 7% of the average). Nevertheless, it seems that the hydraulic retention time has much stronger effects on the SMA than the influent concentration.

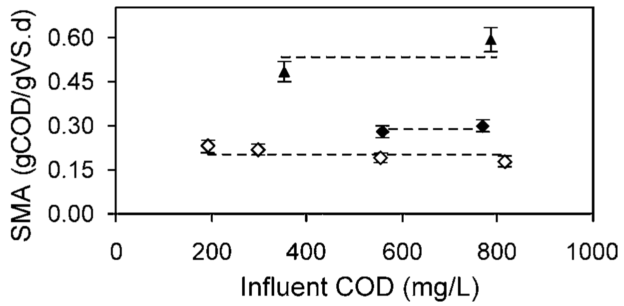

Figure 3.2 – Effect of COD_{Inf} on the SMA The bars represents the range found in the triplicate test

(▲) HRT=2h, (◆) HRT=4h, (◇) HRT=6h.

3.3.2. Sludge Biodegradability

The Effect of HRTime and V_{up} on the Sludge Biodegradability

For the reasons mentioned below, it is obvious that the sludge biodegradability should be high in reactors operated at a short HRT (Figure 3.3).

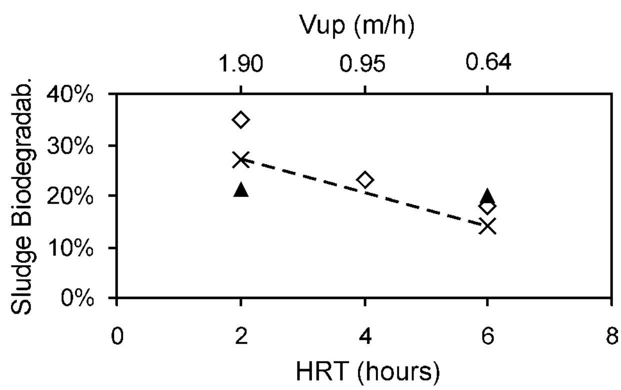

Figure 3.3 – Effect of HRT and V_{up} on the Sludge Biodegradability.
(◇) COD_{Inf}~800mg/L,
(▲) COD_{Inf}~550mg/L,
(X) COD_{Inf}~320mg/L.

(i) Reactors operated at short HRTs are inherently also submitted to high OLR, and in the case of sewage, also generally to a high SS loading rate. This high amount of entrapped suspended solids reduces the SRT, and therefore increases the biodegradability of the sludge.

(ii) Reactors operated at short HRTs are also exposed to a high VFA loading rate (VLR). The high biodegradable material is then due to the high concentration of methanogenic biomass which was grown under the high VLR. VFA is usually present in raw sewage due to some hydrolysis and acidification that occur in the sewer system. Moreover, VFA is also produced in the reactor during the acidogenic step. The effect of HRT on the VFA loading rate is discussed in section 3.4 (results shown in Table 2).

The results in Figure 3.4 show that the first hypothesis may be coherent with regards to the effect of SRT on the sludge biodegradability. Although the SS removal efficiency decreased for reactors operated at shorter HRTs, the SS loading rate (based on the removed SS) was higher.

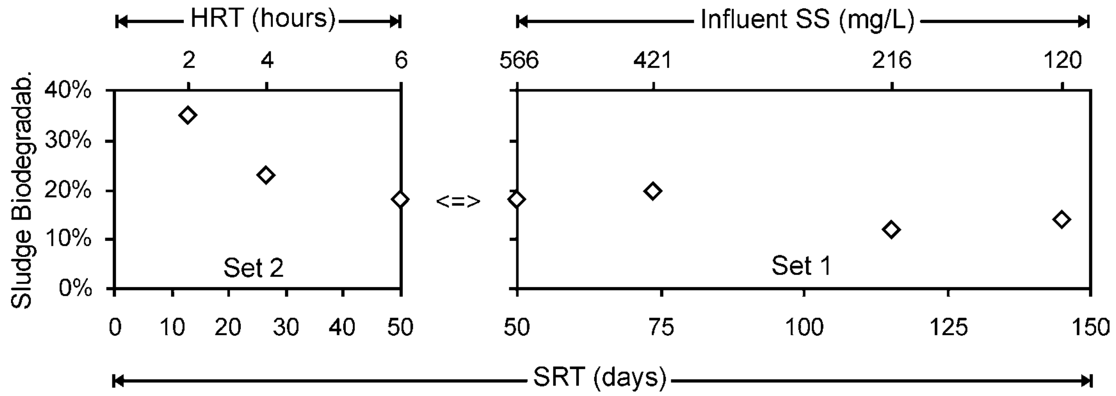

Figure 3.4 – Effect of SRT, HRT and influent SS concentration on the Sludge Biodegradability.

Set 1: Reactors operated with different COD_{Inf}, but at the same HRT (6 hours).

Set 2: Reactors operated at different HRT, but approx. the same COD_{Inf} (~800mg/L).

Yet, the second hypothesis is also consistent. Assuming that the SMA is proportional to the fractional methanogenic bacteria content of the sludge, then for the same sludge biodegradability the differences in SMA only can be attributed to differences in the fractional contents of biodegradable SS of the sludge. This can be confirmed by applying the method described by Mgana (2003) for evaluation of the degradable suspended solids fraction (X_{Deg}) in the sludge. The method requires a linearisation of the curve of the cumulative methane production during the biodegradability test, as presented in Figure 3.5 for reactors R^6_{816}, R^4_{770}, and R^2_{787} (plots A, B and C respectively).

If the stabilisation of the sludge sample had occurred according to single first order kinetics, then the biodegradability would most probably be due to the decay of biomass (X_{bm}). This is because the methane production, after a prolonged test period, originates from bacterial death and subsequent decay of dead cells (Seghezzo *et al.*, 2002), as well as from the decay of poorly biodegradable matter.

The results reveal that the first parts of the curves in Figure 3.5 do not fit in the linearised methane production. This discrepancy can be interpreted as contribution of hydrolysed X_{deg} in addition to the decay of the biomass. It is clear that the discrepancy in Figures 3.5B and 3.5C exceeds that found in Figure 3.5A, indicating that the concentration of degradable suspended solids increased as the HTR decreases.

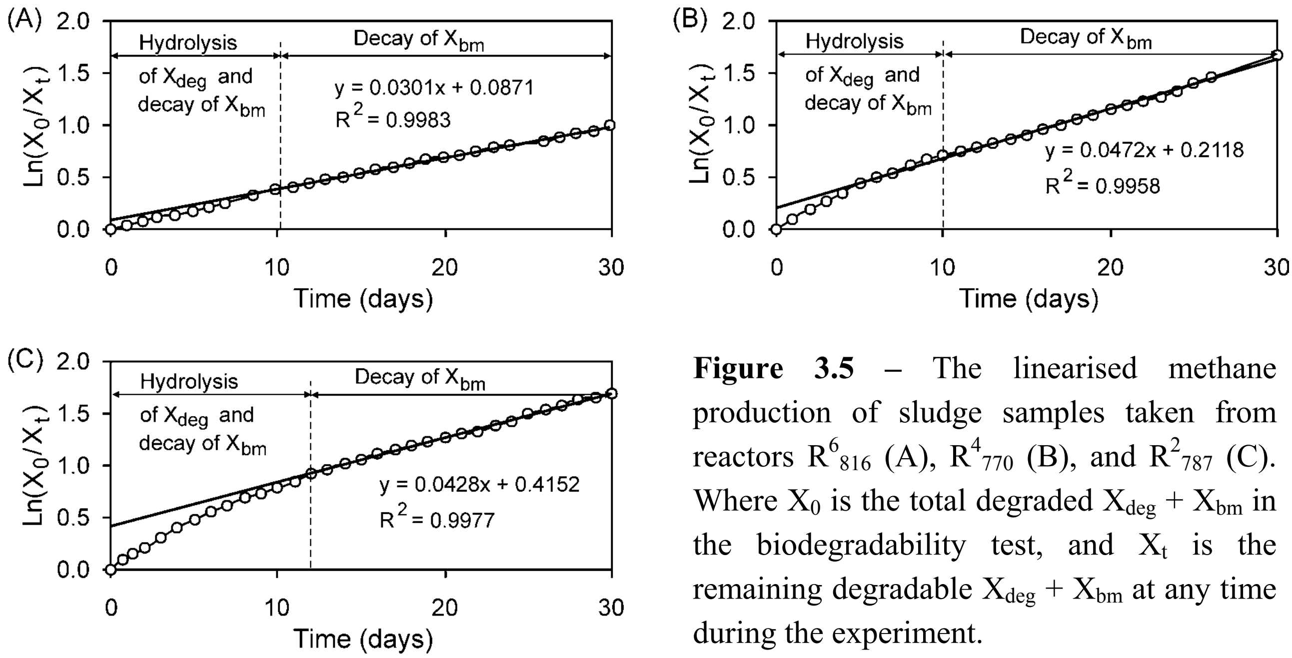

Figure 3.5 – The linearised methane production of sludge samples taken from reactors R^{6}_{816} (A), R^{4}_{770} (B), and R^{2}_{787} (C). Where X_0 is the total degraded $X_{deg} + X_{bm}$ in the biodegradability test, and X_t is the remaining degradable $X_{deg} + X_{bm}$ at any time during the experiment.

The values for the decay constant (K_d) used in the equation in the plots are within the range provided by the literature review of Batstone *et al.* (2002) (from 0.004 to 0.050 d^{-1}). The K_d of sludge produced in reactors R^{6}_{816}, R^{4}_{770}, and R^{2}_{787} amounted to of 0.030, 0.047 and 0.043 d^{-1} respectively. The latter indicates that a significant part of the biodegradability of the sludges of reactors R^{4}_{770} and R^{2}_{787} (Figures 3.5B and 3.5C respectively) is due to degradable SS, and most of the biodegradability of reactor R^{6}_{816} (Figure 3.5A) is due to the decay of biomass.

The Effect of COD_{Inf} on the Sludge Biodegradability

The results depicted in Figure 3.6 show that the reactors operated with low influent concentration produced sludges with a lower biodegradability than reactors that were operated with high influent concentrations. This is because for a given HRT, the low total influent COD, and therewith low SS concentration, leads to a long SRT (Figure 3.4) and therefore the low biodegradability of the sludge.

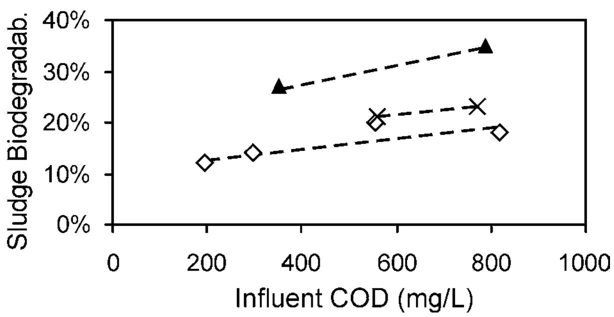

Figure 3.6 – Effect of COD_{Inf} on the Sludge Biodegradability.

(▲) HRT=2h,

(X) HRT=4h,

(◇) HRT=6h.

3.4. FINAL DISCUSSION

The Effect of HRT and COD_{Inf} on the Sludge Biodegradability

According to the Environmental Protection Agency (EPA, 1995), anaerobic sludge is considered stable if the VS content is reduced by less than 17% in a bench test for 40 days at a temperature between 30 and 37°C.

The results presented in Figures 3.3 to 3.5 show that the sludges of reactors operated at an HRT of 6 and COD_{Inf} below 500mgCOD/L are stable based on the standards established by the EPA. Moreover, the sludges produced in reactors operated at HRT of 6 and 4 hours and with COD_{Inf} exceeding 500mgCOD/L barely exceed the levels of biodegradability established by EPA for landfill disposal, ranging from 18 to 23%. However, the sludges produced in reactors operated at 2 hours are much more biodegradable (27-35%), and further treatment might be necessary to achieve the required stability for, e.g. landfill disposal.

The Effect of HRT and COD_{Inf} on the Maximum Methanogenic Potential

Maximum Methanogenic Potential (MMP) is the maximum capacity of a reactor to convert an imposed VLR into methane under optimal conditions. MMP is determined using Equation 3.3. The VLR was calculated based on the influent VFA concentration and the VFA produced by acidogenesis in the reactor (Equations 3.4 and 3.5). The difference between the MMP and VLR gives the "extra" VFA loading capacity, or the "reserve" capacity of the reactor to convert the VFA (introduced and/or produced) during a possible VFA overload. The MMP provides an insight into the capacity of the reactors to withstand a certain overload. The results present in Table 3.2 show that the "extra" VFA loading capacity significantly increases in systems operated at lower HRTs, which is an indication that it is useless to design an UASB reactor with long HRT in order to increase its capacity to cope with shock loads.

Table 3.2 – Maximum Methanogenic Potential (MMP) and VFA Loading Rate (VLR) during the "steady state" conditions.

Parameter	Reactors							
	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^4_{770}	R^2_{787}	R^4_{558}	R^2_{352}
Sludge mass - M_X (gVS)	2104	1950	1366	1162	2291	2332	2231	1866
SMA (gCOD/gVS.day)	0.18	0.19	0.22	0.23	0.30	0.59	0.28	0.48
Max Meth. Potent. – MMP (gCOD/h)	15.8	15.4	12.5	11.1	28.6	57.3	26.0	37.3
VLR during "steady state" (gCOD/h)	10.5	7.5	4.6	2.4	11.9	21.2	10.0	10.6
Extra VFA loading capacity (gCOD/h)	5.3	7.9	7.9	8.7	16.7	36.1	16.0	26.7

$$MMP = \frac{SMA \times M_X}{24} \quad \text{(Eq. 3.3)}$$

$$VLR = \left(COD_{Inf}^{VFA} + COD_{Acid}^{VFA}\right) \times Q \quad \text{(Eq. 3.4)}$$

$$COD_{Acid}^{VFA} = A_{Tot} \times COD_{Inf}^{Tot} \quad \text{(Eq. 3.5)}$$

$$A_{Tot} = \left(COD_{CH4} + COD_{Eff}^{VFA} - COD_{Inf}^{VFA}\right) / COD_{Inf}^{Tot} \quad \text{(Eq. 3.6)}$$

Where: MMP is the maximum methanogenic potential (gCOD/h), SMA is the specific methanogenic activity (gCOD/gVS.day), M_X is mass of volatile solids in the reactors (gVS), VLR is the VFA loading rate (gCOD/h), COD_{Inf}^{VFA} = Influent VFA as COD (gCOD/L), COD_{Acid}^{VFA} is the VFA produced during the acidogenic step (gCOD/L), and Q is the flow rate (L/h), A_{Tot} is the acidogenesis based on total influent COD (COD_{Inf}^{Tot}), COD_{CH4} is methane gas production in production terms of COD (gCOD/L), COD_{Eff}^{VFA} is the total VFA in the effluent as COD (gCOD/L), COD_{Inf}^{VFA} is the total VFA in the influent as COD (gCOD/L).

3.5. CONCLUSIONS

Based on the results presented in this chapter, it can be concluded that:

(i) Lower imposed HRT leads to a higher sludge SMA, which can be attributed to a better selection of the sludge at higher upflow velocities, and a high concentration of biomass that was grown under the high VFA loading rate.

(ii) The influent concentration in the range of 200-800mgCOD/L (with a fraction of SS in the range of 65 – 75%) hardly affects the SMA

(iii) The Maximum Methanogenic Potential of the system decreases at decreasing influent concentrations and/or increasing HRTs. In contrast, the "reserve loading capacity" (or the capacity of the reactors to convert an overload of VFA) increases as the influent concentration decreases and/or HRT decreases. This is an indication that there is no merit in designing an UASB reactor with long HRT in order to increase its capacity to cope with shock loads.

(iv) Reactors operated with a long HRT and with a low COD_{Inf} produce sludges with low biodegradability, i.e. a highly stabilised sludge. Only the sludges produced in UASB reactors operated at HRT of 6 hours and with COD_{Inf} below 500mgCOD/L are sufficiently stable based on the requirements of the EPA for landfill disposal.

(v) The high biodegradability of sludges produced in reactors operated at a low HRT is due to the high amount of entrapped degradable SS and the high concentration of biomass.

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4

THE EFFECT OF OPERATIONAL CONDITIONS ON THE HYDRODYNAMIC CHARACTERISTICS OF THE SLUDGE BED IN UASB REACTORS

This work aims to evaluate the hydrodynamic properties of the sludge bed of Upflow Anaerobic Sludge Blanket (UASB) reactors based on its settleability (compactability) and expansion characteristics. To achieve this goal, the methodologies used for the evaluation of the settleability of aerobic activated sludge, and for the expansibility of a sludge bed of Expanded Granular Sludge Bed (EGSB) reactors and Fluidised Bed Reactors (FBR) were adapted and applied to the particular characteristics of the granular or flocculent sludge of UASB reactors. An easy-to-build experimental set-up was developed to assess the parameters necessary for the equations of Vesilind, 1968 (settleability) and of Richardson and Zaki, 1954 (expansibility). The results obtained from the sludges of seven differently operated reactors show that the parameters obtained using this experimental set-up can be used to calculate the settleability (compactability) and expansibility of anaerobic sludge using the equation aforementioned. Moreover, it was found that the different operational procedures led to different sludge settleability (compactability) and expansion characteristics, i.e. settleability increased and expansibility decreased at decreased hydraulic retention time (HRT) and/or increased influent concentrations. The results show that it is worthless to design an UASB reactor with a longer HRT to cope with hydraulic shock loads. Finally, the procedure developed during this work gave more accurate information than the SVI method.

4.1. INTRODUCTION

One of the main advantages of the Anaerobic Upflow Sludge Blanket (UASB) reactor is its capacity to retain a high quantity of viable biomass for long periods under operational conditions (sludge age >> hydraulic retention time). This is a result of the installation of a gas-liquid-solid separator in the upper part of the reactor, and of the sludge granulation (or flocculation) process which occurs in the system. The success of the UASB system also thus lies in the highly settleable type of biomass that develops in the system.

One of the parameters frequently used to evaluate the settleability of an anaerobic sludge is the Sludge Volume Index (SVI). This is due to easiness of the procedure. However, the use of SVI in assessing the settleability of a sludge is controversial: according to several authors (Giokas *et al.*, 2003; Jin *et al.*, 2003; Bye and Dold, 1999, 1998; and Dick and Vesilind, 1969) this parameter has a bad correlation with the settleability characteristics of the aerobic sludge. The latter authors also agreed that a more accurate procedure for the evaluation of the settleability seems to be the one developed by Vesilind (1968), which is based on the relationship between the solids zone settling velocity (ZSV) and the sludge concentration. This method generates two empirical parameters, namely "k" and "$U_{S,0}$", which provide insight into the hydrodynamics of the aerobic sludge particles (or flocks). However, there are no reports about the use of this kind of test for anaerobic sludge. In this case, several researchers have used SVI to assess the settleability, including Mahmoud (2002), Martínez *et al.* (2001), Ince *et al.* (2001), Wang and Shen (2000), Yun *et al.* (2000), and Grotenhuis *et al.* (1991).

An important characteristic of anaerobic reactors that are operated in an upward-stream mode is the expansibility of the sludge bed. There are several papers dealing with sludge bed expansion, but only the Expanded Granular Sludge Bed (EGSB) reactors and Fluidised Bed Reactors (FBR) were used during all the investigations (Nicolella *et al.*, 1999; Marín *et al.*, 1999; Setiadi, 1995; Diez Blanco *et al.*, 1995; Hermanowicz and Ganczarczyk, 1983; and Ngian and Martin, 1980;). Particularly for UASB reactors, these parameters may be related to the capacity of the reactor to retain the sludge, either during steady state operation at relatively high upflow velocities, or during organic or hydraulic overloading. In fact, the hydrodynamic behaviour of the sludge bed in UASB reactors is still not sufficiently clear. This lack of information has made the design and operation of such reactors to be completed by trial and error, at least with respect to the appropriate sludge bed height or the space between the sludge bed and the phase separator.

This work aims to evaluate the hydrodynamic properties of the UASB sludge bed based on its settleability (compactability) and expansibility. To achieve this goal, the methodologies used for the evaluation of the settleability of aerobic activated sludge, and for the expansibility of the sludge bed of EGSB and FBR reactors were adapted and applied to the particular characteristics of the granular or flocculent sludge of UASB reactors. Sludge samples obtained from seven of the pilot-scale

UASB reactors described in Chapter 2 were used, enabling the test and evaluation of the effects of the different operational conditions on the hydrodynamic properties of the anaerobic sludge.

4.2. MATERIAL AND METHODS

Anaerobic Sludge

The experimental investigation was carried out, using sludge obtained from 7 out of the 11 pilot-scale UASB reactors described in Chapter 2 (height 4.0m, internal diameter 0.2m, and volume 120L). The pilot-scale reactors were operated at a temperature of 27±1^{o}C, and were fed with pre-screened domestic sewage from Campina Grande city (Brazil). The parameters used to operate the reactors are presented in Table 4.1. Once a “steady state” situation (see details in Chapter 2) was established, sludge samples were withdrawn from taps located at four heights of the reactor (0.25, 1.00, 1.75 and 2.50 meters from the bottom), and these samples were mixed to assemble a composite sample of the reactor sludge.

The experiments with the sludge of the reactors, i.e. the assessment of the sludge bed profile, sludge settleability (compactability), and sludge expansion, were always conducted at the end of the operational period of all reactors, lasting more than three times the sludge retention time.

The pilot-scale reactors operated in this work were denominated by $R^{HRT}{}_{COD}$, where the superscript index stands for the hydraulic retention time, and the subscript index stands for the total influent COD (chemical oxygen demand). Both are the average during the “steady state” conditions.

Lab-Scale Reactors

The experimental set-up was comprised of 2 lab-scale UASB reactors constructed from plexiglass tubes, with a volume of 7.8L, a height of 1.2m and internal diameter of 0,08m. They had a modified gas-solid-liquid separator as described by Cavalcanti (2003), and were equipped with a recirculation pump. A slowly rotating stirrer (1rpm) was installed in the lab-scale reactors to avoid channelling and “piston” formation in the sludge bed, as recommended by Dick and Vesilind (1969), for settling tests in small cylinders. Figure 4.1 shows a schematic diagram of the lab-scale UASB reactors.

Experimental Procedure

The composite samples of the sludge were analysed for total solids (TS), volatile solids (VS), and SVI prior to the test in the lab-scale reactors. Then 2.5 litres of this composite sample were used in each of the two lab-scale reactors (the experiments were done in duplicate). Next, these reactors were filled up with anaerobically treated effluent and recirculation was started. The recirculation pumps were adjusted to such a flow rate that the upflow velocity (U) was the same as in the pilot-scale reactor from where the sludge was withdrawn. The lab-scale reactors were maintained with this operation until almost no gas was released. The next steps were to increase or decrease the upflow velocity, by re-adjusting the recirculation pumps, and to collect data of sludge bed heights and times, until there was almost no variation in the bed height. The upflow velocity was increased until the sludge bed reached the gas-liquid-solid separator, and decreased by factors of 0.5, 0.75 and finally recirculation was stopped (U = 0), and the minimum height was observed.

All physical-chemical analyses were performed as recommended by APHA, 1995. Raw samples were used for the determination of the total COD of the influent of the pilot-scale reactors. The sludge volume index (SVI) assessed in this work refers to the diluted SVI developed by Stobbe (1964).

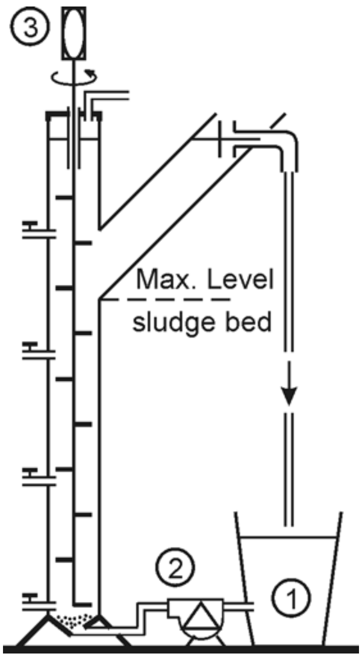

Figure 4.1 – Schematic diagram of the lab-scale UASB reactors.

Legend:

(1) Treated wastewater tank,

(2) Recirculation pump,

(3) Stirrer.

4.3. RESULTS AND DISCUSSION

4.3.1. Sludge Settleability (Compactability)

An example of results that can be obtained using the aforementioned methodology is depicted in Figure 4.2A, where the sludge samples withdrawn from the pilot-scale reactor R^1_{716} (operated with upflow velocity of 3.8m/h) was tested for different upflow velocities in the lab-scale reactors. Sludges taken from all reactors mentioned in Table 4.1 were tested following this procedure.

During tests with the sludge from reactor R^1_{716}, the upflow velocity (U) in the lab-scale reactor was first adjusted to 3.80m/h (the same upflow velocity imposed to the pilot-scale reactor R^1_{716}). After a certain time, the gas production stopped and the height of the sludge bed stabilised at a level of 46.5cm (see dashed line in Figure 4.2A). The upflow velocity was then set at 5.70m/h until the sludge bed stabilised at another level (51.5cm), and subsequently the pump was again set at 3.8m/h until the level of the bed achieved its former position. This procedure was repeated for upflow velocities of 1.90 and 0.95m/h. The case of U=0m/h was also tested, which represents the maximum contraction of the sludge. In Figure 4.2B the results of the sludge bed height after stabilisation for each upflow velocity is depicted.

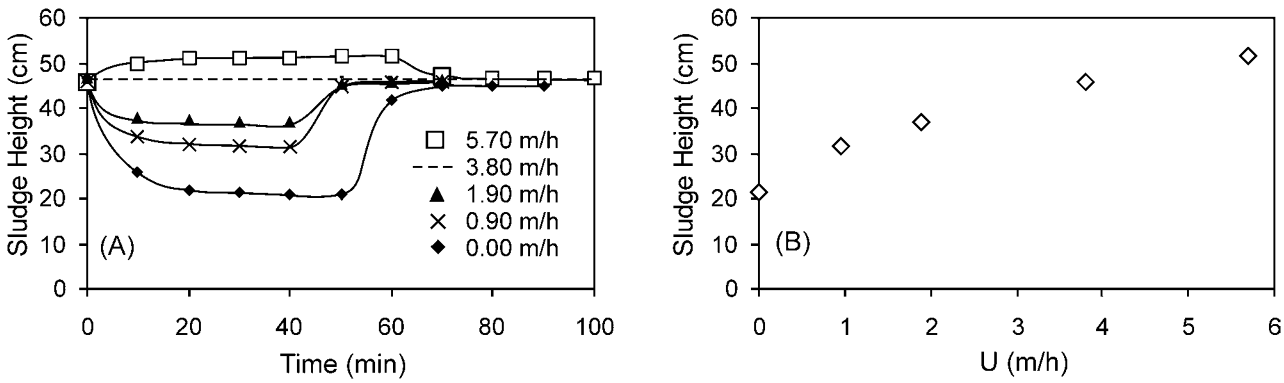

Figure 4.2 – Variation of the sludge bed height (sludge taken from reactor R^1_{716}) due to changes in upflow velocity (U). (**A**) Variation with the time; dashed line represents the normal upflow velocity in the pilot-scale reactor R^1_{716}. (**B**) Sludge height for different upflow velocities applied to the lab-scale reactors after stabilisation of the expansion or contraction.

The sludge concentration of the composite sample was determined prior to conducting any tests, and consequently the sludge mass was known. Since the volume of the sludge bed is proportional to the bed height, there was a different volume for each upflow velocity, and accordingly a different sludge bed concentration (see Equation 4.1).

With the calculated results of X using Equation 4.1 and the method developed by Vesilind, 1968, viz. plotting Ln(U) versus X, a straight line results using the least squares method. On the basis of this line, a direct relationship is obtained, as presented in Equation 4.2. Figure 4.3 depicts the results of the calculated sludge bed concentration (X) and Ln(U) from all the sludge samples taken from the seven UASB reactors.

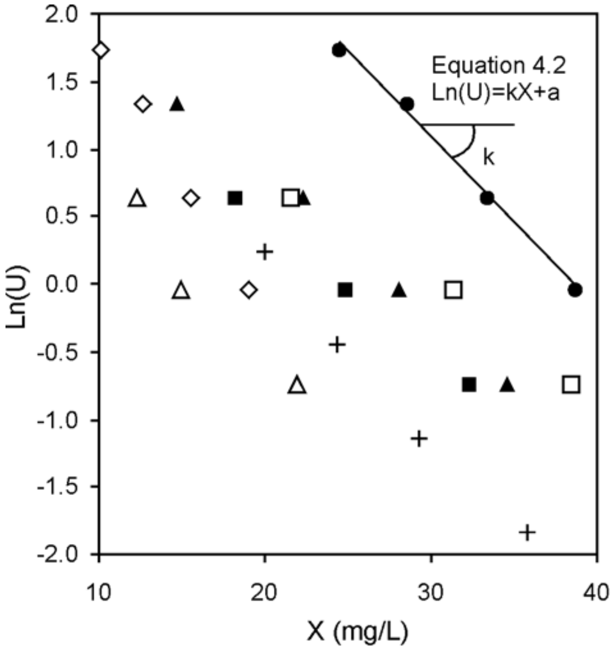

Figure 4.3 – Results of the calculated sludge bed concentration “X” and Ln(U) of all sludges taken from the 7 UASB reactors. The straight line for the sludge of the pilot-scale reactor R^1_{716} was plotted as illustration.

$$X = \frac{X_0 \times V_0}{A \times h} \qquad \text{(Eq. 4.1)}$$

$$\mathrm{Ln}(U) = k.X + a \qquad \text{(Eq. 4.2)}$$

Equation 4.2 can be expressed in the form of:

$$U = U_{S,0} \times e^{(k.X)} \qquad \text{(Eq. 4.3)}$$

$$U_{S,0} = e^{a} \qquad \text{(Eq. 4.4)}$$

Where X is the sludge concentration for a given sludge bed height (g/L); X_0 is the sludge concentration of the composite sample (g/L); V_0 is the volume of sludge used for the experiment (2.5 L); “A” is the cross-section area of the lab-scale reactor ($0.5 dm^2$); and h (dm) is the height of the sludge for a given upflow velocity; U is the upflow velocity (m/h); $U_{S,0}$ (m/h) and k (L/g) are the Vesilind empirical constants (see Table 4.1); and “a” is an empirical constant.

Considering that in equilibrium conditions, i.e. a constant sludge bed height, the applied upflow velocity (U) is equal to the settling velocity of the sludge bed, then for a given upflow velocity the higher the settleability of the sludge, the higher the sludge bed concentration (X). As the sludge bed of an UASB reactor performed as a hindered structure (not as single particles) during the tests, the settleability of the sludge bed can also be referred as compactability.

Table 4.1 – Operational parameters for the UASB reactor sludge samples investigated in this work, and the results of the calculated constants for settleability (compactability) and expansibility.

Reactor	HRT	U [(a)]	COD_{Inf}	----- Settleability -----			- Expansibility -	
	(h)	(m/h)	(mg/L)	SVI [(b)]	k [(c)]	$U_{S,0}$ [(d)]	m [(c)]	$U_{E,0}$ [(d)]
R^6_{816}	6	0.64	816±45	18	-0.13	16	1.96	0.3
R^4_{770}	4	0.95	770±38	21	-0.10	11	1.59	0.5
R^2_{787}	2	1.90	787±31	22	-0.10	18	1.52	0.8
R^1_{716}	1	3.80	716±42	16	-0.13	135	1.59	3.2
R^4_{558}	4	0.95	558±31	18	-0.08	11	1.27	0.8
R^2_{352}	2	1.90	352±18	18	-0.13	9	1.61	0.3
R^1_{136}	1	3.80	136±18	23	-0.20	47	1.84	0.6

(a) U is the normal upflow velocity applied to the reactors where the sludge was withdrawn. (b) Sludge Volume Index (mL/g). (c) Empirical parameters (L/g). (d) Empirical parameters (m/h). The results of the empirical parameters "m" and "$U_{E,0}$" will be discussed in section 4.3.2.

Figure 4.4 shows the experimental results of the reactors operated at different HRT (R^6_{816}, R^4_{770}, R^2_{787}, and R^1_{716}) and at an influent concentration of around 800mgCOD/L, together with the calculated results using Equation 4.3. When comparing the results of these reactors, the settleability apparently increased as the HRT decreased (and upflow velocity increased), which is possibly due to the occurrence of a certain selection process in the sludge bed, i.e. the washout of the voluminous light flocks, leaving the well-settling aggregates in the reactor (O'Flaherty *et al.*, 1997).

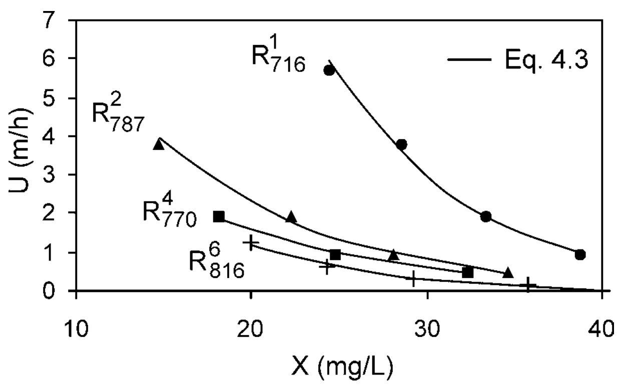

Figure 4.4 – Experimental and calculated results of upflow velocity (U) and sludge concentration (X) for reactors operated with different HRT, but with approximately the same influent concentration (~800mgCOD/L).

Figure 4.5 presents the experimental results of two sets of reactors operated at different influent concentrations, and two different HRTs (R^2_{787} and R^2_{352}: HRT=2h; and R^1_{716} and R^1_{136}: HRT=1h), together with the calculated results using Equation 4.3. For a specific HRT or upflow velocity, the settleability of the sludge increased as the influent COD concentration increased. This phenomenon can be due to at least one of the following reasons:

(i) According to Jia et al. (1996), a low substrate concentration may cause a depletion of the extracellular polymer (ECP) production (known to be one of the responsible factors for sludge granulation or flocculation – Yun et al., 2000; Jia et al., 1996; and Tay and Yan, 1996), which may then lead to a more flocculent type of sludge, thus less settleable (compactable) sludge (Mulder, 2003; Lettinga and Hulshof Pol, 1991; and Lettinga et al., 1980);

(ii) The formation of a type of more flocculent sludge when the reactor is fed with dilute influent, and with relatively low upflow velocities, may be due to a kind of natural selection, as this kind of sludge has lower mass transfer resistance compared to granular types sludge (Nicolella et al., 2000; and Gonzalez-Gil et al., 1997). Therefore, the substrate is more accessible to the biomass in the flocculent sludge.

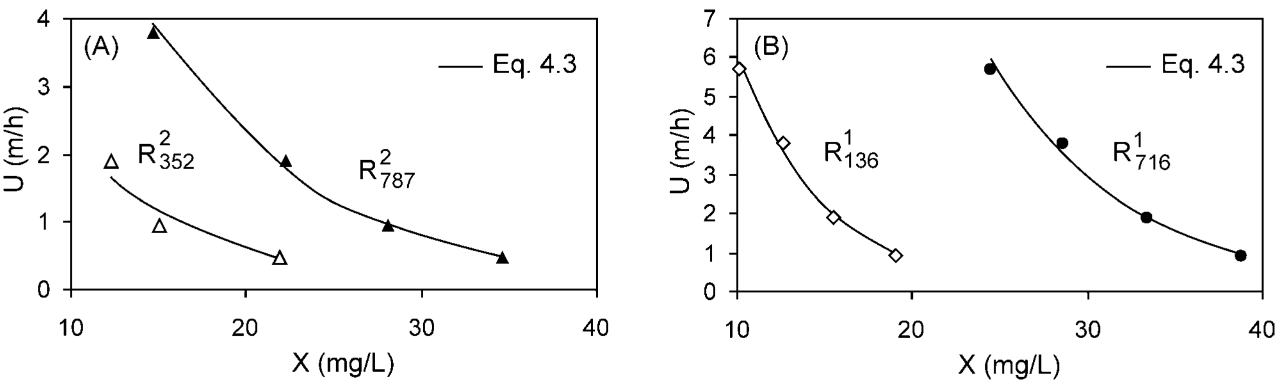

Figure 4.5 – Experimental and calculated results of upflow velocity (U) and sludge concentration (X) for two sets of reactors fed with different influent concentrations, and two different HRT. (**Set A**) R^2_{787} and R^2_{352}. (**Set B**) R^1_{716} and R^1_{136}. The continuous line represents the calculated results obtained by Equation 4.3.

There was no simple and evident correlation observed between the settleability constants ("k" and "$U_{S,0}$") and the Sludge Volume Index (SVI). It is probable that the SVI is not a good parameter for characterising the settleability of sludge, neither anaerobic nor aerobic because: (i) it is not independent of the sludge concentration, (ii) it is highly affected by the experimental set-up and procedure during the test, (iii) it defines only one point of the settling curve, and finally (iv) it is intuitively doubtful that two parameters of a model (Equation 4.3) can be estimated based on only one SVI value from a test performed at a single sludge concentration value (Dick and Vesilind, 1969; Jin *et al.*, 2003; Bye and Dold, 1998; Bye and Dold, 1999; Ekama and Marais, 1986; and Giokas *et al.*, 2003).

The assessed SVI values were correlated with the operational parameters, viz. HRT (Figure 4.6A) and influent COD (Figure 4.6B). However, such correlation hardly exists. With regards to the results of the plots of SVI versus HRT and of SVI versus COD_{Inf}, there is only a slight trend for SVI to decrease when HRT or COD_{Inf} increase. The trend of SVI to decrease with increasing HRT was certainly unexpected, as at lower HRTs, i.e. increased upflow velocity, the retained sludge is intrinsically more settleable. The contradiction may be due to the fact that either the SVI parameter is not appropriate for settleability analysis, as mentioned before, or the range values for SVI found for the anaerobic sludge (16 – 23 mL/g) is too narrow and far lower than the range usually found for aerobic. In fact, Mohlman (1934) developed the SVI method for evaluation of the settleability of the aerobic activated sludge, which in SVI ranges from around 40 to 400 mL/g (Giokas *et al.*, 2003).

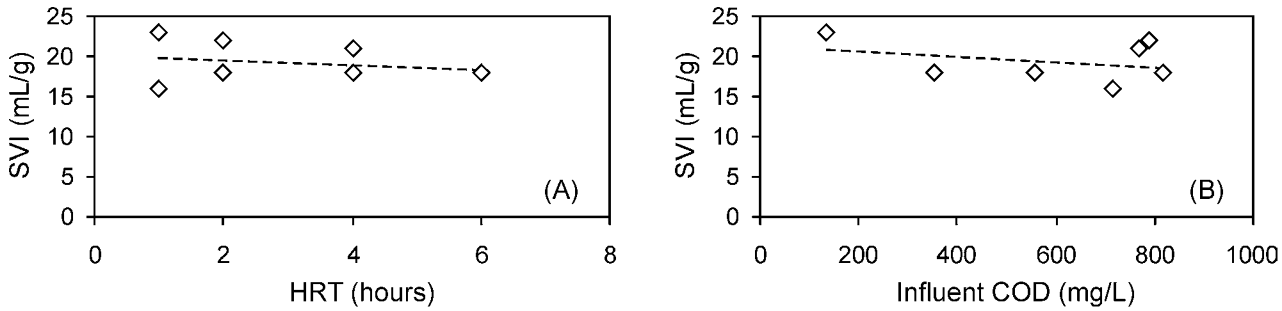

Figure 4.6 – Effect of HRT and influent COD on the Sludge Volume Index (SVI).

4.3.2. Sludge Bed Expansion

The expansion of the sludge bed was calculated using Equation 4.5. Figure 4.7 depicts an example of the calculated expansion (ε) of the sludge sampled from reactor R^1_{716}. The different heights of the sludge bed were established at the various upflow velocities

$$\varepsilon = \frac{h - h_0}{h_0} \times 100 \quad \text{(Eq. 4.5)}$$

Where: ε is the sludge bed expansion (%); h is the established height of the sludge bed for a given upflow velocity; h0 is the height of the sludge when upflow velocity is zero. All heights are in dm.

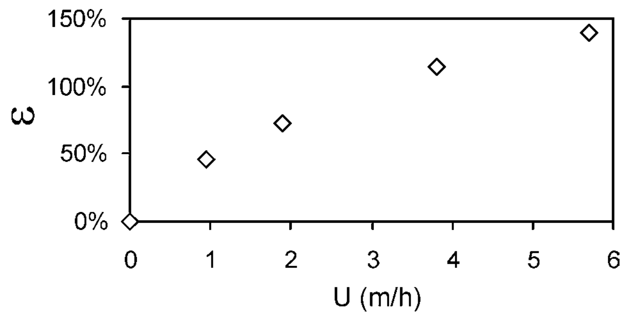

Figure 4.7 – The established relation between the upflow velocity (U) and Expansion (ε) for the sludge sampled from reactor R^{1}_{716}.

The expansion of a specific sludge can be modelled using the methodology developed by Richardson and Zaki (1954), which is achieved by plotting Log(U) versus the calculated values of ε (Figure 4.8). Using the straight lines obtained using the least squares method, the parameters of the linear equation (Equation 4.6) can be obtained.

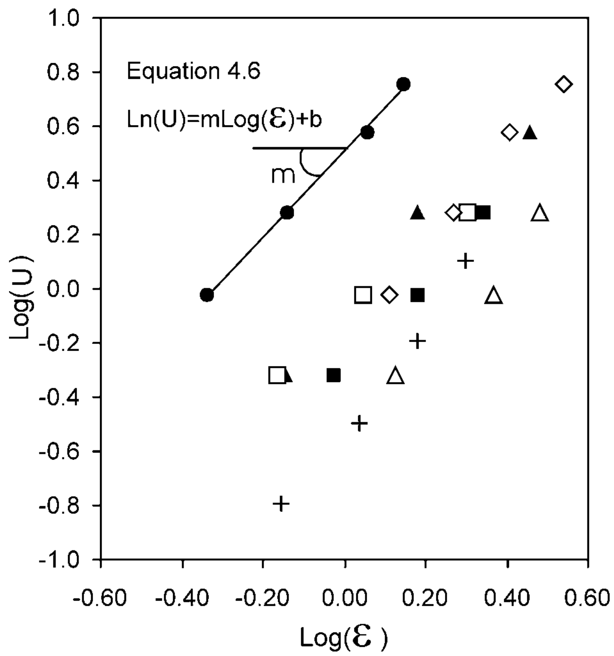

Figure 4.8 – Results of the calculated sludge expansion (ε) and Log(U) of all sludges taken from the 7 UASB reactors. The straight line for the sludge of reactor R^{1}_{716} was plotted as an example.

Legend

+ R^{6}_{816} ■ R^{4}_{770} ▲ R^{2}_{787} ● R^{1}_{716}

□ R^{4}_{558} △ R^{2}_{352} ◇ R^{1}_{136}

$$\mathrm{Log}(U) = m \times \mathrm{Log}(\varepsilon) + b \qquad \text{(Eq. 4.6)}$$

Equation 4.6 can be expressed in the form of:

$$U_i = U_{E,0} \times (\varepsilon)^m \qquad \text{(Eq. 4.7)}$$

$$U_{E,0} = 10^{b} \qquad \text{(Eq. 4.8)}$$

Where UE,0 (m/h) and "m" (L/g) are the expansibility constants (see Table 4.1); U is the upflow velocity (m/h); and "b" is an empirical constant.

Figure 4.9 shows the experimental results of the reactors operated at different HRTs (R^6_{816}, R^4_{770}, R^2_{787}, and R^1_{716}) and at an influent concentration of around 800mgCOD/L, together with the calculated results using Equation 4.7 (represented in the graph by the continuous line). When comparing the results of these reactors it is clear that the sludge expansibility declined at a decreasing HRT.

Expansion is actually highly related to the settleability (compactability) of the sludge, and these two parameters describe the same hydrodynamic characteristics of the sludge bed. The pilot-scale reactors, from which the sludge samples were withdrawn, were operated without intentional sludge discharge, i.e. they were operated under their maximum sludge accumulation capacity. Consequently, the smallest sludge expansion led to a sludge washout. Thus, the sludge remaining in the reactors, which were operated with a high upflow velocity, was less expansible than the sludge present in the reactors operated with a low upflow velocity.

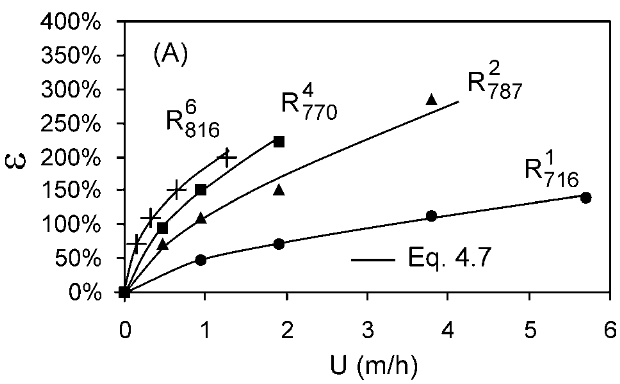

Figure 4.9 – The effect of upflow velocity (U) on the sludge bed expansion (ε) for the sludge of reactors operated at different HRT, but at approximately the same influent concentration (~800mgCOD/L). Continuous line represents the calculated results obtained by Equation 4.7.

Figure 4.10 presents experimental results of sludge bed expansion for two sets of reactors operated at different influent concentration, and two different HRT (R^2_{787} and R^2_{352}: HRT=2h; and R^1_{716} and R^1_{136}: HRT=1h), together with the calculated results using Equation 4.7.

For a specific HRT or upflow velocity, the sludge bed expansion decreases with an increasing influent COD. The reasons for such behaviour should be the same as mentioned for settleability (compactability) analysis, i.e. the low substrate concentration leads to depletion of the ECP production and consequently a more flocculent and less settleable sludge develops; and/or a kind of natural selection that decreases the mass transfer resistance, which makes the dilute substrate more accessible to the biomass.

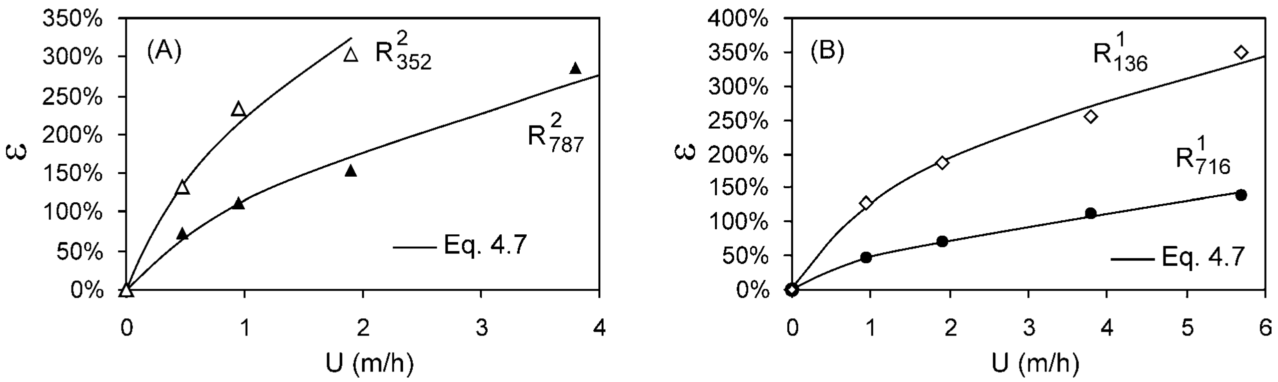

Figure 4.10 – The effect of upflow velocity (U) on the sludge bed expansion (ε) for two sets of reactors fed with different influent concentrations, and two different HRT. Continuous line represents the calculated results obtained by Equation 4.7.

4.4. FINAL DISCUSSION

It is clear that operational conditions significantly affect the hydrodynamic properties of the anaerobic sludge bed. The operation of UASB reactors, like other modern high rate systems, is based on the retention of a high amount of viable biomass. The sludge retention in UASB systems is assured on the development of a well-settleable sludge, which is counterbalanced by the imposed upflow velocity. Thus, the sludge retained in the reactor is intrinsically capable to cope with the imposed upflow velocity. Consequently, reactors operated with high upflow velocities will by principle contain sludge of a relatively high settleability, and consequently a relatively low expansibility. The role of the influent concentration on the hydrodynamic properties of the sludge seems much more subtle. The results of this study shows that UASB reactors treating low influent concentrations lead to the development of a more flocculent type of sludge, which is less settleable (compactable) and more expansible. But, these findings are limited to the type of influent used in this research, i.e. municipal wastewater with a restricted range of SS concentration (100 – 570mgCOD/L), to the applied HRT (1 – 6 hours), as well as to the environmental conditions of a tropical country.

It does not make sense to use SVI for evaluating the settleability of UASB sludge. The parameter SVI was developed for activated sludge, which consists of a completely homogeneous type of sludge produced in a CSTR systems. In contrast to CSTR systems, the UASB reactor uses sedimentation as the driving force, and as a consequence the values of SVI are very low in comparison to activated sludge, and will likely produce an inaccurate assessment. Values of SVI ranging from 10 to 30mL/g are frequently found for UASB sludge, which belongs to the category of highly settleable.

The methodology developed by Vesilind (1968), adapted in the present investigation, can be used for the optimisation of systems that use UASB reactors as pre-treatment. UASB reactors can be operated without intentional sludge discharge, and then the produced (washout of) excess sludge has to be removed from a secondary settler (or from the next treatment unit where it will accumulate). The parameters $U_{S,0}$ and k (Table 4.1) can then be used for the design of this secondary settler. Such an operational procedure of the UASB reactor may improve the filtration capacity of the system, as well as the organic load potential, because the system is then operated with its maximum sludge accumulation capacity. Moreover, by removing the sludge from the secondary settler, the risk of over discharge is avoided.

The model used for the prediction of the sludge bed expansion, which was adapted from the equation of Richardson and Zaki (1954), mainly aims at the optimisation of the sludge bed height in an UASB reactor in the case that the reactor is operated with intentional sludge discharge. If the flow rate fluctuation regime is known, it is possible to predict the variation of the sludge bed height. Therefore, it is possible to avoid any substantial sludge washout during a hydraulic overload, which can deteriorate the post treatment step. As an example: assuming that the UASB reactor has to cope with a variation of as factor of 1.5 the average flow rate (usually found in separate sewer system), and using the data of reactors operated with 6 and 4 hours (upflow velocity ranging from 0.64 to 0.95m/h, and influent concentration ranging from 500 and 800mgCOD/L), the optimal sludge bed height (under "steady state" conditions) should be maintained between 70 to 80% of the distance between the bottom of the reactor and the phase separator.

If the UASB reactors are operated in a mode without intentional sludge discharge, it is possible to quantify the amount of sludge that will be expelled during an imposed hydraulic overload. Thus, either some protective measures – if needed – can be applied in the post treatment, or the post treatment can be designed in such a way that it can cope with the temporary sludge overload.

The test developed to determine the sludge bed settleability (compactability) and expansibility is based on modifications of two consolidated methodologies. However, these adaptations still need to be further standardised, as several parameters can affect the results, including the temperature, the dimensions and configuration of the lab-scale reactor, as well as gas production. In short, further research is needed on the possible effects of these parameters, as well as the statistical significance of the results.

The results in this work show that it is worthless to design a reactor with a longer HRT in order to cope with a hydraulic shock, as a more expansible sludge will develop, which is less able to withstands flow variations.

4.5. CONCLUSIONS

(i) The experimental set-up and the procedure presented in this work are suitable for assessing the settleability (compactability) of anaerobic sludge using the equation of Vesilind, 1968, as well as to assess the expansion of a sludge bed using the equation of Richardson and Zaki, 1954.

(ii) Decreasing HRTs or increasing upflow velocities leads to increased settleability (compactability) and decreased expansion of the anaerobic sludge.

(iii) Decreasing the influent COD concentration leads to decreased settleability (compactability) and increased expansion of the anaerobic sludge.

(iv) The settleability (compactability) test developed in this work can help the design of a secondary settler, which can improve the performance of the system.

(v) The expansibility test developed in this work can be used to optimise the ideal level of the sludge bed, when the UASB reactor has to cope with fluctuations of the flow rate.

(vi) The SVI parameter cannot be used to compare the settleability of sludge of different UASB reactors, since this kind of sludge is highly settleable and seems to be out of range for this method. Moreover, no relation was found between the SVI values and the settleability characteristics of anaerobic sludges.

(vii) It is useless to design an UASB reactor with a longer HRT in order to cope with hydraulic shock loads.

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PART 2 – SHOCK LOAD CONDITIONS

5

THE EFFECTS OF OPERATIONAL AND ENVIRONMENTAL VARIATIONS ON ANAEROBIC WASTEWATER TREATMENT SYSTEMS: A REVIEW

With the aims of improving the knowledge about the stability and reliability of Upflow Anaerobic Sludge Blanket (UASB) reactors, several researchers studied the effects of operational or environmental variations on the performance of anaerobic wastewater treatment systems. In general, anaerobic reactors are affected by changes in external factors, but the severity is dependent upon the type, magnitude, duration and frequency of the imposed changes. Typical responses include a decrease in performance, accumulation of volatile fatty acids, drop in pH and alkalinity, change in biogas production and composition, and sludge washout. This review will summarise the causes, types and effects of operational and environmental variation on anaerobic wastewater treatment systems. However, there still remain some unclear technical and scientific aspects that are necessary in improving the stability and reliability of anaerobic processes.

5.1. INTRODUCTION

This chapter presents a literature review on the types and impacts of several operational and environmental variations on the performance of anaerobic treatment systems. It is also intended to show how scientists have dealt with the aspects of monitoring, modelling and controlling the biological processes, as well as the hydraulics of anaerobic reactors. In the scientific papers, it was verified that each quoted researcher was eager to study the behaviour of a specific reactor. Each researcher also submitted the reactors to a strict range of variations in some operational parameters, generating a dispersed set of information on the subject. To facilitate a thorough understanding of this review, the chapter was arranged by firstly presenting in Section 5.2 the main variation types and classifying them according to their causes, effects and occurrence. Section 5.3 discusses the monitoring, mathematical modelling and controlling of the anaerobic process when operated under steady state and stress conditions. Finally, Section 5.4 presents considerations and comments on behaviours of the anaerobic reactors submitted to environmental variations, which still remain unclear.

5.2. CAUSES AND EFFECTS OF ENVIRONMENTAL VARIATIONS ON ANAEROBIC WASTEWATER TREATMENT SYSTEMS

Wastewater treatment plants (WWTP) are subject to variations on one or more parameters that affect or rule the reactor performance, viz. flow rate, influent type and concentration, sludge retention time (SRT), nutrients availability, temperature, pH, presence of xenobiotics, as well as others. Some of these variations can be predicted and controlled, and the reactor can be designed to accommodate them. But this is not the case for all variations, and the reactor's performance can deteriorate due to extreme transient conditions.

5.2.1. Causes of the Disturbances

In practice, the treatment system can become exposed to many variations, i.e. (1) In case of sewage, the cyclical nature of human activities leads to a variable sewage production over the day (Metcalf & Eddy, 1991); (2) Frequently separate wastewater sewerage has inappropriate connections of runoff water and rainfall contributions, resulting in overloads in networks as well as in down stream treatment plants (Dauphin *et al.*, 1998); (3) Combined sewer networks exhibit the first-flux phenomena, in cases where storm water contributions results in an increased Suspended Solids (SS) and Chemical Oxygen Demand (COD) concentration in the first minutes of the event (Deletic, 1998); (4) The sewage network often has one or more pumping stations, which convey the sewage intermittently at a much larger flow than average (Dauphin *et al.*, 1998); (5) Tourist areas dramatically increase their populations during holidays, leading to high flow rate variations over the year (Castillo *et al.*, 1997); (6) Operational procedures at the treatment plant can result in increased hydraulic and organic loads, viz. when it is necessary to stop one of several anaerobic units for maintenance, the others have to cope with the entire flow rate; (7) Several types of disturbances can manifest in case of industrial wastewater, even under normal operational conditions, given that the flow rate and waste concentration vary with the industrial processes routine (Puñal and Lema, 1999).

Sewage Flow and Composition Variations Over the Day

Domestic wastewater generally shows high flow variations due to the number of inhabitants and dwellings connected to the sewer system, specific characteristics of the sewerage (type, material, length, maintenance, infiltration, use of pump stations), as well as climate, topography, commercial/industrial contributions. The traditional approach to estimate the quantity of wastewater in a separate sewerage assumes a daily flow per capita to give an average dry weather flow, and uses multipliers for estimating the peaks and low flows (Metcalf & Eddy, 1991; Butler *et al.*, 1995; and Campos and von Sperling, 1996). The flow in such type of sewers shows characteristic patterns on annual, seasonal, daily, hourly, and sub-hourly time scales.

In general, the flow of the wastewater in a separated sewer system follows a pattern that can be simplified using the equations presented by van Haandel and Lettinga (1994). However, according to Campos and von Sperling (1996), these kinds of simplifications could lead to misestimates. They presented an analysis of data related to the domestic wastewater characteristics from several areas situated in the large Brazilian city, Belo Horizonte. They found higher flow-rate variations than those usually used for the design of treatment plants, and the extent of the variations is higher in the wealthier areas of the city. They developed models to predict basic wastewater characteristics (water consumption, wastewater production, BOD load and concentration) based on simple socio-economic variables. According to the results of their studies, the main wastewater characteristics vary with the hour of the day and the day of the week, in addition to depending on total family income.

Several researchers have studied the variation of flows and changes in the sewage composition which occur in sewer system and wastewater treatment plants. Heip *et al.* (1997) developed a mathematical model to simulate the hydraulic behaviour of a sewer network. The calibration was done in a city at the north of Belgium utilizing data from a nine-month monitoring campaign. Data from a monitoring station in a small Danish town, which produces 4-5L/s of wastewater, showed diurnal variations between zero and approximately 10L/s during dry weather (Schaarup-Jensen *et al.*, 1998). Oliva (1997) characterised the sewage of São Carlos - Brazil (separate sewer system) on the basis of several parameters, throughout several hours of the day, and different days of the week. Their results show variations of 103% between minimum and maximum COD during the week, and

117% between minimum and maximum COD throughout the day. Higher variations were found in proteins, carbohydrates and lipids contents, 260%, 1003%, and 650% respectively over the week, and 171%, 302%, and 150% over the day.

In many cases, the main source of inflow into sewer networks (separate system) is comprised of domestic wastewater. Sewage however, also generally includes commercial and industrial wastewaters. The domestic fraction of sewage is made up of contributions from various household appliances, influencing flow quantity and quality, and thus the hydraulic and organic load at the end-of-pipe WWTP. The household discharges are mainly derived from the WC, kitchen sink, washbasin, bath, shower, and washing machine. Butler *et al.* (1995) and Friedler and Butler (1996) examined the quality of wastewater generated by each domestic device of 28 households in South East England, and 51 homes in Malta. Generally, the WC is the most significant wastewater-producing appliance, contributing to around 40% of the daily average flow of the household total discharge, and 40% of the total pollution load. By monitoring the wastewater of the several houses, they were able to analyse the daily variation of BOD (38%), Orthophosphate (52%), ammonia (136%) and nitrate (50%), for the case of South East England. Although the authors overemphasise the variations, it seems that they are not as significant when taking into account wave attenuations that occur into the sewer.

<u>Tourist Areas</u>

An important example of the prevalence of considerable changes in flow-rate and organic loading rate (OLR) can be found in tourist areas, where the population increases dramatically during the high season. Castillo *et al.* (1997) studied the feasibility of a combined anaerobic-aerobic system (UASB + RBC) for treating the wastewater of a small tourist village near Barcelona. Experiments were carried out in the summer (tourist season) and in the winter, examining very different loads and temperatures (19^{o}C and 12^{o}C). Results show that removal efficiencies are similar in both seasons, because the higher ambient temperature during summer time balances the higher loads during that season. At high temperatures, the reactor can cope with the imposed higher loading rates. Orhon *et al.* (1999) also presented an example of tourist coastal city in Turkey (Bodrum), where the increase on the population can rise as high as 1500% during the high season. In fact, the effect of this kind of variation depends on the design of the reactor.

<u>First-Flush</u>

The concept of “the first-flush of storm runoff” is based on the assumption that the first part of runoff is the most polluted. Deletic (1998) investigated whether or not this phenomenon really exists and what its characteristics are. To characterise the “first-flush”, researchers usually use curves of the cumulative fraction of the total pollutant mass versus the fraction of total cumulative runoff volume. The phenomenon is perceived if a mass cumulative curve of a pollutant is above the runoff volume curve (Bertrand Krajewski *et al.*, 1998). According to a French study, a strong first-flush very rarely occurs, but in more than 65% of the studied events, this phenomenon manifested to some extent (Saget *et al.*, 1996). In fact, Deletic (1998) did not find a strong first-flush of suspended solids, but it manifested in 30% of the studied events and particularly during large storm events. Such a first-flush could not be assessed for pH or for temperature. The researcher also suggested that the pollutant transformations and transport processes might cause the first-flush.

Independent of the question whether first-flush events really exist, wastewater treatment plants nonetheless are presently not designed for accommodating these types of overcharges. This implies that this extra amount of incoming wastewater is sent through the equalization unit of primary clarifiers, or it is by-passed direct to the water bodies (Carstensen *et al.*, 1998). According to the insights of Bechmann *et al.* (1998), during dry weather there are a deposition of pollutants in the sewer that are flushed out with the first rain contribution. This idea is supported by Bertrand-Krajewski *et al.* (1995), who found that there was an increase of mineral and settleable solids due the catchment's surface wash off during storm events. However, the COD concentration in the influent of the treatment plant remained unchanged compared to that of the dry weather periods. This means that there is a chance for overloading (during a short period), but this conflicts with the view of Deletic (1998). There are actually a number of variables related to the first-flush, primarily based on the characteristics of the catchments and the sewer network. In steep catchments, sediments are typically absent and no erosion can take place. Sediments are present in an flat catchments area, but erosion is limited due to low velocities. In large catchments areas, the first-flush potential is reduced as a result of the long transportation time and wave attenuation phenomenon. Therefore, for catchments, steepness and areas of a medium size, a distinct first-flush will likely occur (Krebs *et al.*, 1999).

5.2.2. Effect of Hydraulic and Organic Load Variations

In anaerobic digestion, a delicate balance exists between the primary processes (hydrolysis and acidogenesis) and the conversion of the acid products by acetogenic and methanogenic bacteria into methane and carbon dioxide (Cohen *et al.*, 1982). According to many specialists working in this field, e.g. van Lier *et al.* (2001), strong variations in flow and concentration may adversely affect the efficiency of an UASB reactor. The effect of fluctuations in hydraulic and organic load generally depend on the applied Hydraulic Retention Time (HRT), Sludge Retention Time (SRT), intensity and duration of the variations, sludge properties, and the reactor design, particularly the design of the three phase separator. Thus far, a clear relationship between the mentioned parameters and the performance behaviour of the UASB reactors operating under environmental variations, has not been fully established.

The accumulation of volatile fatty acids (VFA) can be a typical reactor response during overloading, and sudden variations in hydraulic and organic loading rates. Hydrogen partial pressure plays an important role in controlling the proportion of the various intermediate products of the anaerobic reactions. Under stressful conditions, there may be a shift in the metabolic pathway to a less favourable route, resulting in a ratio shift between VFA producers (acidogens and acetogens population) and consumers (methanogens, sulphate reducing bacteria - SRB, and nitrogen reducing bacteria - NRB). Such a highly undesirable situation could lead to the production of significant amounts of carbon dioxide and hydrogen gas in the biogas. The partial pressure of hydrogen gas inside of the reactor might increase to values exceeding 10^{-4}atm, which may then cause a shift in the metabolic pathway. When slowly growing methanogens cannot sufficiently and rapidly eliminate all H_2 produced by the H_2-producing bacteria (e.g. in case the sludge contains insufficient hydrogen consuming organisms), this may result in a distinct inhibition of the degradation of propionate, butyrate and lactate (Fongastitkul *et al.*, 1994; Cánovas-Díaz and Howell, 1988; Eng *et al.*, 1986; and Cohen *et al.*, 1982). Another typical effect during a situation of stress is the drastic change in biogas production rates and compositions (Chua *et al.*, 1997).

Although some researchers, such as Inanc *et al.* (1999), support the idea that high volatile fatty acids concentration is detrimental for the activity of methanogens, other authors (Cohen *et al.*, 1982) affirm that the effect of high VFA concentrations are better regarded as the result of an imbalance, rather than the cause of reactor destabilisation. In fact, during organic shocks with VFA and glucose in one-phase and two-phase anaerobic reactors, Cohen *et al.* (1982) did not observe inhibition due to a toxic action of VFA, under conditions of a well-controlled pH. The substantial accumulation of propionate observed by Cohen *et al.* (1982) and many other researchers, suggests a saturation of the hydrogen transfer reactions and, as a consequence, an enhanced disposal of electrons via an alternative route. From this information, Cohen *et al.* (1982) presumed that carbon dioxide reduction was the rate-limiting step, rather than the splitting of acetate. They never found a significant acetate accumulation, or lag-period for the degradation of VFA, in any of their experiments with organic shock loads. However, the authors were not clear about the sludge and design of the reactor they used, and inhibition due to VFA would depend on the conditions under which they conducted their experiments, e.g. the type of sludge used, OLR and sludge loading rate, etc.

Borja and Banks (1995) tested the effect of shock loads on the performance of a fluidised bed reactor (FBR) by increasing the flow rate to 100 and 150% during six and twelve-hour periods, utilizing the same influent concentration. The reactor was fed with synthetic ice-cream wastewater, and was operated at an HRT of 8h and OLR of 15.6KgCOD/m^3.day. During the shock, they reported a decrease in pH (from 7.1 to 6.6) and alkalinity, and an increase in the effluent VFA and COD. The gas production thus increased, but the methane content decreased. The change in the

CH_4/CO_2 ratio was a direct consequence of an inhibition of methanogenesis, and of the decreased solubility of CO_2 at the low pH values (Fongastitkul *et al.*, 1994; and Eng *et al.*, 1986). In the same investigation, Borja and Banks (1995) also tested the increase of the influent COD to 100 and 150% during six and twelve hours. The effects were essentially the same as found in the experiments with hydraulic load variations, but less pronounced. When they increased the concentration of the influent, they also increased the buffering capacity so that the pH remained well controlled. The most severe shock imposed to the system was conducted by increasing the influent COD by 150% during 12 hours, which caused an increase of 180% in effluent COD. This is not so severe, unless the system already was overloaded prior to the shock. However, the reactor recovered its normal performance within 11 hours after the shock ceased. The authors did not supply enough information about the sludge for a good evaluation about overloading, but it seems that the reactor could cope well with the imposed shocks. This kind of reactor actually performs well at higher OLRs (Holst *et al.*, 1997; and Borja *et al.*, 1995), which means that the shocks were likely assimilated by the reactor “buffer” load capacity.

Bhatia *et al.* (1985a,b) investigated the response of a step change in concentration and flow rate in a 9.8 litres UASB reactor, using a synthetic wastewater composed of acetic, propionic and butyric acids. The changes were accomplished by varying the concentrations from 600 to 900mg/L of each acid separately during 12 hours. The authors carried out other step-change-like tests by increasing the flow rate from 1.0 to 11.8L/h until the reactor achieved a new steady state. They concluded that the reactors took approximately one residence time for recovering from the imposed changes in loading rates, which means that delays decreased when the flow rate increased. This behaviour could be due to mass transfer resistance, as the diffusivity increases after a hydraulic shock load (Brito and Melo, 1999). Another effect observed by Bhatia *et al.* (1985a,b) was the existence of different levels of effluent concentration (at “steady state”) for the same operational condition. This phenomenon (hysteresis) was perceived when the researchers increased the flow rate from 1.0 to 11.8 L/h, and then decreased it back to 1.0 L/h. The effluent concentration for the same flow rate was lower when the flow was increased. The authors attributed the hysteretic effect to the structure of the cultures inside of the flocculated biomass, which can change depending upon the operational condition. However, it is likely that the K_S (Monod half saturation constant) increased when the OLR was raised, and did not return to previous values when the OLR was decreased.

Several researchers suggested that the diffusivity of substrate through a biofilm is function of liquid velocity and substrate concentration. Under steady-state conditions, the diffusivity increases with a higher substrate concentration (Fick’s law) and decreases with a higher flow velocity (Beyenal and Lewandowski, 2000). According to the authors, the substrate concentration has a stronger effect on the diffusivity than the flow velocity. With regards to the effect of flow velocity on the diffusivity, there is a contradiction between Beyenal and Lewandowski (2000) and Zaiat *et al.* (1996), who found that the external mass transfer resistance can be decreased by increasing the flow velocity. Brito and Melo (1999) investigated the sensitivity of the internal mass transfer coefficient in fully established biofilms to a transient shift in the external bulk liquid velocity. They found that at a constant and laminar flow, the diffusivities do not depend upon the flow rate. However, under conditions of turbulent liquid flow and thus higher shear stresses, the flow velocity has a pronounced effect on the biofilm thickness and compactness, leading to different mass transfer coefficients. Moreover, if the bulk liquid suffers a shift in the velocity, there is an average increase in internal mass transfer coefficient.

Chua *et al.* (1997) investigated the response of an anaerobic fixed-film reactor (AFFR) to hydraulic shock loads. The reactor was operated with synthetic dairy wastewater – having an influent COD of 3g/L and an HRT of five days. Shocks with duration of seven days were imposed by reducing the HRT from 5.0 days to 2.5, 1.25, 1.0 and 0.5 days, and with a concomitant decreasing of the influent concentration. They suggested that the ability of this type of reactor to cope with the imposed shocks was due to the fixed biofilm, which was not washed out during critical hydraulic shock loadings. Even so, the AFFR took four days to recover from hydraulics shocks of only twice the flow rate, and the authors did not mention why methanogenic bacteria were inhibited during the shocks, combined with VFA accumulation in the reactor. It was likely that the dilutions necessary to maintain the same organic load at an increased flow rate affected the methanogenic activity.

Eng *et al.* (1986) described experiments in an UASB reactor (12.7L) fed with diluted leachate liquor (~2.2gCOD/L) and operated with HRT around 6h. They were interested in testing the capacity of an anaerobic digester to cope with severe shock loads such as those caused by accidental spillage of sugar syrup in a sugar beet processing industry. Shock loads with sucrose at different concentrations (10, 12 and 50 g/L) and different durations (3 and 8 days) were applied. In all experiments, the reactor-pH dropped to around 4.7, causing the inhibition of methanogenesis. The researchers concluded that the UASB system is potentially vulnerable to shock loads, but methanogenesis resumed few days after the shock load ceased, as long as alkalinity is provided. However, the authors were not clear about the use of leachate to simulate the wastewater of sugar beet processing industries, and did not mention the shock due to a distinct carbon source – the reactor was adapted to diluted leachate (VFA rich influent) and the shock were imposed with sucrose. It seems that the UASB reactor was more robust than the authors affirmed, as it was expected that the reactors would completely fail when operated under a shock load of 5 times the "steady state" influent concentration over a three-days period, using a different carbon source in the influent.

Oliva (1997) conducted experiments in an 18m^3 UASB reactor treating sewage from the city of São Carlos, located in the southeast of Brazil. They exposed the system to several shocks by increasing the flow rate (Q) by 50% twice a day, and 100% once a day. According to the results they presented (not shown in this review), it appears that the reactor tended to become better adapted after each imposed shock. This observation can possibly be attributed to the washout of the fine sludge ingredients, or less dense particles during the imposed first shocks. During the 2xQ shock, the effluent COD increased until the load was returned to its basic value, but the 1.5xQ shock did not seriously affect reactor performance.

Castillo *et al.* (1997) investigated the effect of different HRTs on a pilot-scale UASB reactor (750L), fed with domestic wastewater (COD_{Inf}~600mg/L), under winter (~13^{o}C) and summer (~20^{o}C) conditions. Their results show that the removal efficiencies of total, soluble fraction and suspended fraction of COD increase as the HRT increases, but there is a trend to become constant for an HRT higher than 6 hours. After every change on OLR (imposed by increasing the HRT), the reactors passed through a transient condition before they achieved the new "steady state". It is worthwhile to note that anaerobic reactors operated at lower temperatures were more sensitive to organic variations.

Kalyuzhnyi *et al.* (1996) investigated the performance of a lab-scale UASB reactor fed with synthetic wastewater composed of sucrose (2g/L), potassium acetate (2-5g/L as acetic acid) and mineral medium. The reactor was operated under organic loading rates ranging from 3.4 to 44.9 gCOD/L.day, at HRTs ranging from 4.0 to 22.5 h, at a temperature around 36^{o}C, and was fed with influent concentrations ranging from 3.2to 7.5 gCOD/L. The reactor was inoculated with suspended sludge withdrawn from another reactor treating milk industry wastewater. They found that increasing the OLR up to 44.9gCOD/L.day, at HRT=4h, caused an almost complete disappearance of lighter granules in the reactor. Furthermore, they found that at a lower OLR, the granules mainly consisted of filaments of *Methanothrix* cells; whereas a change in the population occurred at a higher OLR, showing the significant presence of *Methanosarcina*, as well as and others *rods* and *cocci*. During the transient condition (the period between the time when the shock started and when the reactor achieved a new "quasi-steady-state"), the reactor's performance deteriorated, resulting in sludge flotation, destruction of granules, and accumulation of VFA. The time for recovering the "quasi-steady-state" conditions ranged from 4 to 22.5 HRT, and it seems that there is a trend to decrease recovery time as HRT decreases, except when the reactor was highly overloaded. They did not explain why this phenomenon occurred, but perhaps the exponential increase of the biomass overcame the linear increase of the OLR, and thus every single step change on the loading rate was accompanied by a relatively higher biomass concentration, which decreased the recovery time.

Nadais *et al.* (2000) investigated the treatment of dairy wastewater by lab-scale UASB reactors operated in an intermittent mode, viz. 48 hours of feeding followed by 48 hours without feeding. The reactors were inoculated with flocculent sludge previously adapted and the temperature was kept around 35^{o}C. They imposed a step-change on the organic load by increasing fat concentration from 2.7 to 4.8g/L (increase of 78%), and from 2.7 to 6.1g/L (increase of 126%). The increase of

78% on the fat concentration did not produce any remarkable effects on the performance of the reactor, and the increase of 126% on fat concentration only caused a small decrease of the COD removal efficiency from 93% to 85%. The researchers also tested a step-change on organic load by decreasing the HRT from 12 to 6 hours, and found an immediate drop on the efficiency (from 93 to 69%). From their results, it can be concluded that the stabilisation period ("feedless" period) has an important role on the stability of the reactor during transient conditions.

Another interesting effect of hydraulic and organic shocks is the rapid decrease in the number and length of free filamentous microorganisms at increased loading conditions, which in anaerobic digesters can represent several different species of acidifiers, acetogens, and methanogens. The decrease in number of such organisms suggests washout or disaggregation of these bacteria during a shock load (Alves *et al.*, 2000). Cheng (1992) studied the morphology of attached biofilm bacteria as a function of organic loading, VFA concentration, and biogas production in a fluidised bed reactor. He found that the filamentous bacteria were predominant at lower organic loading rate (OLR), while the number of *rods* and *cocci* increased at higher OLR and VFA concentrations.

5.2.3. Effects of Variations on the Reactor Temperature

The effect of temperature shocks on reactors depend upon factors such asg the exposed temperature, duration of shock, sludge characteristics, and imposed specific sludge load. At temperatures exceeding that of the maximum growth, the decay rate will generally exceed the bacteria growth rate, and consequently a decrease in specific sludge activity and reactor efficiency may occur (van Lier *et al.*, 1990).

When an anaerobic digester is operated under steady-state conditions, the activities of different metabolic groups are in balance, and consequently there is no accumulation of metabolic intermediate products in the reactor. However, when the process is exposed to a sudden temperature change, the digestion process conditions can become unbalanced due to the different response of the various metabolic groups of microorganisms (Cha and Noike, 1997).

According to Borja and Banks (1995), a shock change in temperature may be characterised by an immediate pH drop in the reactor, which then would stabilise at a value slightly below the previous steady state pH value. This drop in pH is due to an increase of the mixed liquor (effluent) VFA-concentration, which tends to approach a new level during operation at a reduced temperature. The effluent COD increases due to the increase of effluent VFA concentration and suspended solids (SS), as well as to the presence of components in the influent, which remained un-converted.

Investigations of van Lier *et al.* (1990), conducted in a UASB reactor at 39^{o}C fed with synthetic wastewater, dealt with temperature shocks of 45, 55, 61, and 65^{o}C which were imposed during 5, 7, and 24 hours periods. They found that the methane production rate only remained at a high level at

45^{o}C, while exposure to higher temperatures resulted in a serious drop in the activity of mesophilic granular sludge due to high bacterial decay. An increase in methane production manifested immediately after raising the temperature of the system. However, a sharp drop soon followed in cases where the reactor was exposed to temperatures exceeding 45^{o}C. Propionate oxidizers were found to be the most sensitive microorganisms to temperature increments, and methanogens were found to be more sensitive than acidogens. These conclusions are in line with those of Visser *et al.* (1993b), who investigated the effect of temperature shocks in a mesophilic UASB reactor treating sulphate-rich wastewater. Their results revealed that increasing the temperature to 45^{o}C did not affect degradation rates, but temperature elevations to 55^{o}C and 65^{o}C resulted in a sharp decline of the treatment efficiency. On the other hand, according to the results of Rintala and Lepisto (1997), who conducted the methanogenic activity test with thermophilic sludge (55^{o}C) at temperatures of 35, 50, 55, 58, 65, and 70^{o}C, there was some methane production during the first hours of the tests at 65 to 70^{o}C. However, this production slowed down and/or stopped 30 hours later. No significant methane production was found at 35^{o}C until the end of the test, 70 hours later.

Omil *et al.* (1997) investigated the competition between sulphate-reducing bacteria (SRB) and methane-producing bacteria (MPB) at two different pH levels, and exposed the system to short-term temperature decrease. They concluded that temperature shocks of 15 – 12^{o}C for three days in an UASB reactor operated at 30^{o}C and pH 7.75 - 8.0 caused only an insignificant decrease in COD removal efficiencies. The short-term low temperature changes had no effect on the competition.

El-Mashad (2003) performed experiences to assess the effect of temperature fluctuation on the thermophilic anaerobic digestion of cow manure. The author used a CSTR system operated with different HRTs (10 and 20 days), and with different temperatures (50 and 60^{o}C). The fluctuations were imposed by decreasing the temperature in 10^{o}C for a period of 10 hours, and increasing the temperature in 10^{o}C for a period of 5 hours. The results show that temperature fluctuation significantly affects the pH and free ammonia concentration, which in turn, negatively affect the hydrolysis, acidogenesis and methanogenesis steps of the anaerobic degradation of cow manure.

Variations on temperature can also affect the entrapment capacity of the sludge bed, as the temperature changes the viscosity, and consequently changes the hydraulic shearing force on the particles (Mahmoud *et al*., 2003).

5.2.4. Effects of pH Variations

It is well known that methanogenic activity is more likely to proceed optimally in a narrow pH value range, between 6.3 and 7.8 (van Haandel, 1994; and van Haandel and Lettinga, 1994). The effect of a drastic pH-change in the influent depends on the available alkalinity in the reactor. Tests carried out by Borja and Banks (1995) showed that during a 10 hour-period, neither an influent pH of 10 nor an influent pH of 3 significantly affected the reactor stability. This was because the buffer capacity of the system suffices to maintain the pH of the medium in the reactor in the optimal range. In experiments dealing with the treatment of a synthetic wastewater containing VFA and sulphate, Visser *et al.* (1993a) concluded that methanogenesis was inhibited at a medium-pH exceeding 8, which then resulted in the development of a sludge dominated by sulphate-reducing bacteria. They also concluded that sulphate-reducing bacteria are less sensitive to short-term (8 hours) pH variations than methanogenic bacteria.

Moletta *et al.* (1994) tested an on-line automatic system for pH control of an anaerobic fluidised-bed reactor. Some of the tests applied to the system can be useful for exemplifying what occurs to an anaerobic reactor during a small change in pH. They first injected HCl to lower the reactor pH from 6.8 to 6.6, and found an immediate response, viz. the gas production increased 40%, as well as the concentration of CO_2 in the biogas. The hydrogen content remained almost unchanged. They also tested the reactor by adding NaOH to increase the reactor pH up to pH=7.4, and observed that the gas production increased, but the CO_2 concentration substantially decreased. The variations on gaseous phase were the consequence of the shift on the CO_2 equilibrium.

According to Lettinga *et al.* (2000), based on experimental results obtained with sugar beet wastewater, the process efficiency almost immediately recovered from pH-shocks, once the influent pH is returned to the optimal range. In the case of sudden drastic changes, the recovery of the process depends on the extent and duration of the imposed change, as well as on the concentration of volatile fatty acids during the event.

5.2.5. Effects of Contribution with Specific Compounds

Variation of the Carbon Source

A good example of drastic variations that an anaerobic reactor may face concerns the sharp fluctuations in the composition of the wastewater subjected to treatment, e.g. such as those occurring in multi product food-processing industry. Schmidt and Ahring (1997) investigated the treatment of these types of wastewater using an UASB reactor for an industry that was processing throughout the season, viz. peas, carrots, celery roots and leeks, which obviously resulted in four very different types of wastewaters. Four lab-scale UASB reactors were started with the individual wastewaters. Significant differences in the activities and the numbers of microorganisms from different metabolic groups were found. After the reactors reached steady state performance, they were fed with one of the other three wastewaters. Significant decreases in the overall efficiency were observed when the feed was changed from celery wastewater to one of the other wastewaters, which could be attributed to a significant increase in the organic loading rate of the reactor. Such an effect of the performance was also found when leek wastewater, which has a high content of lipids and proteins, was fed to the reactor. The researchers proposed some strategies to overcome the problems caused by these drastic fluctuations in the composition (very frequent in practice), such as an interruption of feeding the reactor, the introduction of adapted granules to the system, and the use of a buffer tank. However, the solutions proposed by Schmidt and Ahring (1997) are difficult to apply. An interruption of the feeding would mean that either the wastewater would be discharged without being treated, or would be stored in a buffer reservoir. The introduction of adapted granules would indicate that these granules would be available in the beginning of the production of the new type of wastewater - which is troublesome as it is difficult to maintain a great amount of adapted sludge for a long period, and it is expensive to transport a great amount of that sludge from another reactor. Thus it seems that the solution of the problem is through another type of treatment configuration.

Yang and Anderson (1993) tested three UASB reactors fed with acetate, sucrose, and ice cream in order to assess the long-term effect of distinct wastewater composition on the UASB stability. Three reactors were inoculated with sludge that had been previously adapted to sucrose. After a steady state was achieved, two of them were fed with different carbon sources, i.e. synthetic acetate wastewater and synthetic ice cream wastewater. With the exception of the carbon source, all other operational parameters (influent COD, flow rate, temperature and nutrients addition) were kept similar within all reactors. During the 400 days of operation, the OLR was gradually increased from 3 to 29 KgCOD/m^3.day. The results revealed all reactors behaved similarly with rates of up to 10.5KgCOD/m^3.day. However, a further increase in OLR led to the deterioration of reactors fed with sucrose, which included a decreased specific methanogenic activity, excessive non methanogenic biomass, predominance of long filamentous bacteria on granules surface and sludge washout. In general, variations of the carbon source present in the wastewater caused gradual changes in the physical structures, bacterial distribution and settling characteristics of the granular seed sludge. But, under certain conditions of OLR, changes on the carbon source can lead to the disintegration or floatation of granular sludge.

Fukuzaki *et al.* (1995) tested four different substrates, viz. starch (1.5 to 3.9 gCOD/L); sucrose (1.25 to 2.5gCOD/L); ethanol (2.0 to 7.0gCOD/L); butyrate (1.5 to 2.9gCOD/L) plus propionate (1.5 to 3.0gCOD/L), to assess the long-term effect of distinct wastewater composition on UASB stability. They used lab-scale UASB reactors that were operated at 37^{o}C and inoculated with granular sludge previously acclimatised on synthetic wastewater containing starch (1.5g/L). The results revealed that variations in the carbon source present in the wastewater caused changes in the physical structures, chemical contents (extracellular polymeric substances), and bacterial distribution. The researchers imposed a change in the influent composition of two reactors, viz. the carbon source was changed from starch to sucrose, resulting in sludge floatation and gradual washout, drops in the pH, and the collapse of the reactor. On the other hand, when the change was from sucrose to starch, no noticeable effect was observed.

Long-Chain Fatty Acids

When an AnWT system is exposed to a sudden overloading with long-chain fatty acids (LCFA), the risk exists that the sludge quality will deteriorate due to a serious drop in methanogenic activity as a result of inhibition (Hwu *et al.*, 1996; Koster, 1989; and Rinzema *et al.*, 1989). The reactor stability can then hardly be maintained, and granular sludge may deteriorate further. In addition to inhibition, some researchers observed severe sludge floatation at lauric acid concentrations exceeding 100mg/L (Koster, 1989; and Rinzema *et al.*, 1989). Floatation resulted from the poor release of gas bubbles by the granules, due to the adsorption of LCFA at the surface of granular sludge. Moreover, the adhered LCFA film may hamper the supply of substrate to the bacteria present in the grains. Another harmful effect is the disintegration of sludge aggregates that can occur when lipids are present. This is because at a neutral pH, LCFA acts as surfactant, lowering the surface tension, and consequently decreasing the aggregation of hydrophobic bacteria. Accordingly, this surfactant effect also cause disaggregation of acetogens, examples of hydrophobic bacteria, that can degrade the long-chain fatty acids (Alves *et al.*, 2000).

Detergents

Detergents belong to the category compounds that are ordinarily discharged down the drain into municipal sewer systems and via this route, enter the sewage treatment plants. These detergents contain surfactants, which decrease the surface tension when added to a mixed system such as water and air, or water and soil. However, according to investigations of Matthijs *et al.* (1995), a distinct biodegradation of these compounds may proceed in the sewer. This results in the significant reduction (up to 47%) of the amount of surfactants disposed into the environment, or those that reach the treatment plant. However, specific industrial effluents, such as those from breweries (Nagel *et al.*, 1999), dairies (Eide *et al.*, 2003), and paper and textile industries (Alvarez *et al.*, 2003), contain cleaning products (such as detergents) at concentrations that can cause toxicity or inhibitory effects on biological treatment (Nagel *et al.*, 1999; and Khalik *et al.*, 1988). Important attention has to be paid to the linear alkylbenzene sulphonates (LAS), as it is one of the most frequently applied surfactants (de Wolf and Feijtel, 1998; and Prats *et al.*, 1997) and it can inhibit anaerobic digestion (Mensah and Forster, 2003; and Mösche and Meyer, 2002).

Despite the fact that it is very probable that WWTPs may periodically have to deal with a shock load of detergents, there is very little research that covers this subject. However, if an overload of detergent occurs, it is likely that a significant fraction is retained in the sludge bed by adsorption (Jensen, 1999), while the remained passes through the reactor without being treated. The inhibitory effect of the surfactants on the active biomass depends upon the adsorbed fraction, as well as the exposure time (Mösche and Meyer, 2002).

Mensah and Forster (2003) examined an anaerobic filter under shock loads of detergent. A mixture of three different detergents was used to impose the shock, e.g. a concentrate washing up detergent, a non-biological hand washing, and a fabric softener. The researchers imposed a shock load adding 2mL/L of the mixture to the base feed (starch and trace elements) over 12 hours. During the experiment there was little change on pH (8.4) and alkalinity (1300mg$CaCO_3$/L). However, after seven hour of shock, the reactor's performance started to deteriorate, viz. the effluent COD and VFA concentrations increased steadily and the methane production decreased, showing that the reactor would fail completely if the shock would not cease after 12 hours.

Nagel *et al.* (1999) investigated the response of a lab-scale UASB reactor under the shock of detergent. The reactor was inoculated with granular sludge from a treatment plant of a brewery, and operated at an HRT of 13.3h. The temperature was maintained between 30 and 35^{o}C. The influent was the wastewater from the same brewery mixed with nutrients. Researchers imposed three pulses of detergent (phosphoric acid and biodegradable non-ionic surfactant) with different concentrations viz. 0.1, 0.4, 0.6%v/v, representing the concentration found at the industry where the sludge was from. They observed that there was a harmful effect on the reactor's performance, i.e. the methanogenic activity was inhibited and VFA concentration increased, but the system easily recovered as soon as the shock ceased.

Oxygen

Methanogenic bacteria located in sludge granules were found to be well protected, and demonstrated a high tolerance for oxygen. However, it must be noted that this protection can mainly be attributed to the presence of oxygen-consuming facultative bacteria in the immobilised consortia. They metabolise part of the available substrate and remove the oxygen, thus creating anaerobic microenvironments. Kato (1994) concluded from his studies that the presence of dissolved oxygen at a concentration of 3.8mgO_2/L in the influent of an UASB and an Expanded Granular Sludge Bed reactor (EGSB) has no detrimental effects on the anaerobic treatment of low strength wastewaters.

5.2.6. Effect of the Duration and Frequency of "Disturbances"

In practice, various specific disturbances can occur in either the form of occasional pulses (Huang *et al.*, 2000), or step changes in the concentration of a polluting component of wastewater, in the flow rate (Nachaiyasit and Stuckey, 1997a; b), or in the temperature, buffer capacity, pH, etc.. These variations frequently manifest in wastewaters originating from industries that use sequential operations or handle various raw materials, e.g. tanneries (Wiegant *et al.*, 1999), breweries

(Austermann-Haun *et al.*, 1998), or food-processing industries (Schmidt and Ahring, 1997 and Hawkes *et al.*, 1992). However, sharp fluctuations can also manifest periodically in domestic sewage, such as those due to human activities, and to climate conditions (van Haandel and Lettinga, 1994). As a result of these factors, a variety of fluctuations in flow rate and compositions frequently occur, These fluctuations sometimesproceed smoothly enough to enable the operator to make the proper measures in the operation of the treatment systems. At other times, the fluctuations occur as a shock and the system needs to have sufficient “buffer” capacity to absorb these instantaneous changes, in order to avoid a drastic reduction in the effluent quality or, in extreme cases, a complete system collapse.

It is difficult to classify the variations with respect to duration, as they can range from a few hours, up to many days, or even longer. The definition of pulse and step-change need to be related to the operational conditions of the treatment system, because they depend upon the technical features of treatment systems. For example, an imposed change of two days can be defined as a step-change for a reactor operated at an HRT of four hours, while it is a pulse in the case of a stabilisation pond, which is operated at an HRT of ten days.

An imposed stress condition can also be related to the changes they cause on the biological population, viz. the sludge characteristics. Thus far, little relevant information can be found about changes in specific sludge characteristics due to imposed changes in environmental conditions.

El Farhan and Shieh (1999) investigated the response of a lab-scale fluidised bed reactor (FBR) towards single and multiple-pulse overloading, and towards step changes (considering a pulse time > 1 HRT will be defined as step change). The reactor was operated at an HRT of 20 hours and fed with glucose plus nutrients (total organic carbon - TOC of 5.2g/L). The single pulse experiment was carried out by increasing the concentration to 200% during a period of 16 hours. The concentration in the step change was also raised to 200%, but for periods lasting 25 and 60 hours. The multi-pulse experiments consisted of three sequential pulses with a duration of six hours, with six hours between the pulses, and another at three pulses of 12 hours, with 12 hours between the pulses. The authors affirmed that at similar loadings, the impact of a multiple-pulse overloading on the FBR performance was more pronounced than that of a single-pulse overloading. But considering their results, the effects of the 60-hours single pulse and the 3x12-hours multi-pulse (60 hours in total) were essentially the same. This may be attributed to the fact that the time between the pulses (12 hours) was not enough to wash out all the sub-products. During the 60-hours single pulse, the pH drops from 6.9 to around 6.2, which did not occur during the multi-pulse. This may perhaps be due to the fact that the total organic load shock during the single pulse was higher (3pulses x 12h/pulse x 15.6gTOC/L x 0.036L/h = 20.2gTOC) than the organic load shock during the multi-pulse (1pulse x 60h/pulse x 15.6gTOC/L x 0.036L/h = 33.7gTOC).

Xing *et al.* (1997) examined the effect of a long-term (>400 days) periodic substrate perturbation on an anaerobic CSTR. This was achieved by introducing an influent with 16 g/L of glucose plus mineral nutrients during three days, followed by glucose-free (COD = 0) mineral influent at the same flow rate for the next three days, maintaining an average concentration of 8 g/L throughout the entire duration of the reactor operation. Another reactor (control) was operated at an influent concentration of 8g/L. Both reactors were maintained at an HRT of 10 days and at a temperature of 35^{o}C. The sludge obtained from a "mother" reactor with TSS of 15g/L had been adapted to the same conditions as the control reactor. During the operational period, the response of the reactor could be subdivided into four distinct phases, viz. during the first 49 days of the operation a rapid accumulation occurred of the metabolic intermediates of the glucose fermentation, consisting of VFA, hydrogen and ethanol. In the next phase, which lasted 240 days, the reactor reached a so-called "metastable steady state" characterised by reduced COD removal efficiency (41%) compared to the control reactor (95%). Following this long operational phase, the system was suddenly capable of degrading the formed VFA, viz. within a period of 30 days, and from there the reactors could be operated at a high COD removal efficiency. From the experiments described in that paper, it is not clear how and why the reactor suddenly behaved so differently after such a long period of operation. The performance of the perturbed reactor, and the methanogenesis, started to improve when the hydrogen concentration decreased and pH increased from 6.1 to 7.1. However, no additional buffer was provided. The results of the experiment show that it is possible to treat a wastewater with high substrate fluctuation if enough buffer capacity is present.

5.3. MONITORING, MODELLING AND CONTROL OF ANAEROBIC PROCESSES

Models of biological processes have been developed with the aims of improving scientific insight as well as better enabling an explanation of the proceeding biological conversion processes. This is true not only with regards to performance characteristics of the reactors, but as well as to fundamental microbiology and biochemistry. The general intention is to use the models for the optimal design of a treatment system, as a tool for process optimisation, and as a method for reducing extensive and complex experimental data to simple and manageable equations (McCarty and Mosey, 1991).

Anaerobic processes, like other biological conversion processes, are quite susceptible to sudden operational changes, which sooner or later may lead to a process failure. Emphasis therefore should be placed on accomplishing early failure detection, so that a pre-emptive remedial action could be taken to bring the process back to its normal operation. Mathematical models can assist in describing and – possibly also in predicting - shock behaviour as well as the design of safeguard control systems (Marsili-Libelli and Beni, 1996).

Several authors have attempted to develop the "ideal" mathematical model that adequately describes the anaerobic process for a certain range of conditions and situations. Pavlostathis and Giraldo-Gomez (1991) and McCarty and Mosey (1991) have extensively discussed kinetic equations, rate constants, mass-balances, and conversion coefficients used to describe anaerobic processes. They also attempted to elucidate the concepts behind the equations, and the ways that these equations can be linked to build mathematical models. In order to reach their objectives on modelling, researchers imposed several kinds of disturbances to the digestion process in their reactors, viz. comprising variations in pH, temperature, presence of xenobiotics and oxygen, fluctuations in hydraulic and organic loading rate, and the use of substrates like glucose, vinasses, VFA, amongst others. However, several of these investigations are quite specific for certain operational situations or types of reactors. Nevertheless, many of these researches are very useful examples of how anaerobic reactors behave when exposed to several types of shock.

A generic anaerobic digestion model (ADM1) was developed by the IWA Anaerobic Digestion Modelling Task Group in order to increase the application of such tool for design, operation and optimisation of anaerobic treatment plants, as well as to serve as a common basis for further developments and validation studies (Batstone *et al.*, 2002a,b). The ADM1 is based on a number of equations that describe the biochemical reactions (extra and intracellular) and the physico-chemical reactions (precipitation was excluded).

Marsili-Libelli and Beni (1996) developed a simplified mathematical model for the behaviour of anaerobic filter. This model focuses on shock loading conditions, with a special emphasis on the importance of bicarbonate alkalinity as a control parameter to minimise the adverse effects of organic load shocks. The model also includes a set of dynamic equations and an extended ion balance to describe the effect of alkali, volatile fatty acids and carbon dioxide. Simplifications for the model were necessary as the anaerobic digestion process is highly complex. For example, only acetic acid was considered as VFA in the acidogenic stage. In addition, with respect to the hydrolytic fermentative phase and the acetogenic phase, it was decided to consider them as one group of acidogens, producing acetic acid. Furthermore, they merely considered a soluble type of substrate, they approached the hydraulic regime as consisting of a completely stirred tank reactor (CSTR), and they also assumed a complete absence of any viable microorganisms in the feed stream.

Nonetheless, the model developed by Marsili-Libelli and Beni (1996) uses six dynamic variables: organic substrate, acidogenic and methanogenic bacteria, acetic acid, and carbon dioxide in both liquid and gas phases. For calibration and validation of the model, they conducted experiments in an anaerobic filter with the following design parameters: HRT=11.5h; volume=333L; OLR=9.7kgCOD/m^3.d; Q=0.481L/min; recycle rate=20ml/min; influent concentration of approximately 4.5gCOD/L. The shocks were imposed for a period of eight hours by increasing the influent concentration to 9.1 and 12.5gCOD/L, and during ten minutes by increasing the influent concentration to 82gHAc/L. Additional experiments were also carried out in order to create a bicarbonate-dosing controller. The agreement between data and model response was considered satisfactory. The investigation of Marsili-Libelli and Beni (1996) comprises one of the few studies that specifically deal with modelling of organic shock loads.

Denac *et al.* (1990) operated lab-scale fluidised bed reactors of 3.6 litres, fed with diluted molasses, at temperature of 35^{o}C, and at an HRT of 6 hours. The objective of their research was to develop an algorithm which would maintain the effluent quality and reactors' stability by controlling the influent pump and adding of NaOH. They imposed step change shocks by increasing the OLR from 12 to 42 g/L.day. After imposing the higher OLR, the NaOH consumption increased from 10 to 35 mg/h in the first 30 minutes, and the total acids concentration in the effluent of the uncontrolled reactor increased from 100 to 900 mg/L in the first 12 hours. In the controlled reactor, the acidity remained bellow 400 mg/L. In fact, the proposed algorithm could regulate the stability of the reactor when the organic load increased, but the rules for the scenario of a drop in feed concentration is quite contestable – it increases the flow rate to keep the system at constant loading and maximum turnover. Moreover, it is only appropriate for soluble and easily biodegradable wastewater.

Several researchers reported that the hydrogen concentration in the gaseous phase could be correlated to instabilities in the anaerobic reactors. Huang *et al.* (2000) investigated the influence of organic shock loads on H_2 production in an UASB reactor using ethylene glycol, acetaldehyde and raw sewage as feed. Results obtained in these investigations indicate that biogas parameters such as H_2 concentration and biogas production rate are the more sensitive parameters, i.e. more than pH, COD and TOC. Thus according to these researchers, these parameters should be used as indicators for shock loadings in UASB. However, molecular hydrogen is produced in the liquid phase, and then transferred to the gaseous phase, which implies that the monitoring systems based on gas measurements depend on the hydrogen-transfer dynamics. According to Pauss and Guiot (1993) and Pauss *et al.* (1990), the rate of hydrogen mass transfer is limited in anaerobic upflow sludge bed reactors because of the low solubility of H_2 and the poor mixing conditions. Furthermore, any correlation between the liquid-to-gas phase hydrogen ratios and operational and hydrodynamic conditions was not observed. Based on this observation, they recommended the use of dissolved hydrogen in bulk liquid as the parameter to control anaerobic reactors, rather than the hydrogen content of the gaseous phase. However, it is obvious that when H_2 is beyond normal levels, the reactor is already in trouble. Consequently, the operator has the problem that the actions he takes may already be too late to recover the steady state condition of the reactor.

Puñal *et al.* (1999) conducted experiments in an anaerobic hybrid reactor (upflow anaerobic sludge blanket - upflow anaerobic filter) equipped with on-line measurement devices such as biogas flow meter, feed and recycling flow meters, thermometer, biogas analyser (CH_4 and CO), hydrogen analyser and pH-meter. In addition, they measured other parameters with the help of off-line equipment such as alkalinity, COD and VFA. Some experiments were performed to assess the response of the bioreactor to an organic overload, and to determine which parameters are feasible in detecting failures. The monitoring of CO concentration did not make sense for predicting the deterioration of the bioreactor. However, they found that H_2 concentration was quite a sensitive variable, and accordingly, they recommended using H_2 together with other parameters such as methane composition or gas flow rate. Moreover, they found that alkalinity provides immediate information about the state of the plant.

According to Pavlostathis (1994) and Marchaim and Krause (1993), the ratio of propionic acid to acetic acid represents a good indicator for detecting digester unbalance due to overloading or organic shocks. This is because they observed an immediate increase of the propionic/acetic ratio prior to any other parameter responding to a 'shock', such as biogas production and composition, pH, and VFA. They performed several experiments with four lab-scale CSTRs, operated in batch mode at thermophilic conditions, and fed with glucose plus nutrients. Shock loads of glucose were imposed under different conditions and the previous mentioned parameters were monitored to assess which of them indicate the beginning of the overload effect. However, as in the case of monitoring the H_2 in the bulk liquid, the propionic/acetic ratio shows an already imbalanced reactor, as this ratio is a result of the H_2 concentration.

5.4. FINAL CONSIDERATIONS

Based on the information reported in this chapter, it can be concluded that operational and environmental variations exist and will always exert an effect on wastewater treatment systems. It is clear that the reactor response varies significantly, not only depending on factors related to the treatment system (reactor configuration, ratio organic load and organic load potential, available alkalinity, and availability of a fault detection and control system), but also on factors related to the variation itself, viz. type of the imposed shock, its extent, frequency and duration.

In general terms, it can be said that anaerobic reactors behave in a similar way when exposed to some abrupt change in operational or process conditions. The typical response is an incomplete methanogenesis, resulting in a certain accumulation of VFA (mainly propionate and butyrate), drop in pH value and alkalinity, change in the biogas production and composition (increase on the CO_2 and H_2 gas content), and sometimes, higher sludge washout.

Organic load variations can be divided into two different classes, those which are due to suspended solids variation, and those due to dissolved solids variation. Each class has their own distinct effects. An extra contribution in the load of SS can lead to a decrease in SRT and further deterioration of reactor performance. However, the effect of SS shock load on the SRT is not clear. Overloading due to dissolved degradable compounds can lead to an accumulation of VFA, a drop in pH values, and possibly an inhibition of methanogenic activity.

In UASB reactors, hydraulic load variations affect the dynamics of the sludge bed. They expand the bed due to a new equilibrium between the upflow and sludge settling velocities. Depending on the variation, a higher SS concentration in the effluent can be expected due to the washout of lighter biomass, the decreased filtration capacity of the sludge bed at higher upflow velocities, and the disintegration of granules or flocks under the abrasive action of shear forces. The treatment capacity can also deteriorate, due to the little contact between the sludge bed and the substrate. During an increase in upflow velocity, the mass transport rises and can also cause an organic overload, which consequences were discussed previously.

Variations in temperature can dramatically affect the performance of anaerobic reactors because of the different response of various metabolic groups of microorganisms. A drop in the activity of methanogens occurs at temperatures lower than 16^{o}C, which can lead to an accumulation of VFA and a drop in pH. Moreover, hydrolysis significantly slows down below this temperature and an accumulation of inert suspended solids in the reactor can occur, leading to a decreasing SRT and deterioration of sludge quality. An increase in the temperature can increase the decay rate of methanogenic bacteria (more sensible to temperature variations) to values exceeding the growth rate. This undesirable situation deteriorates the reactor performance.

A variation of the influent pH value can affect the reactor performance, but it is dependent upon on the buffer capacity of the mixed liquor. Methanogenic activity has its optimum pH value within the range of 6.5-7.5, but acidogenic bacteria are less sensitive to higher or lower pH values. This means that methanogenic activity can become inhibited at a lower pH, while VFA still are produced, which may end in the acidification of the reactor.

Fluctuations in wastewater compositions have immediate effects on the performance of reactors, as the balance of different metabolic groups of microorganisms depends upon the composition of the wastewater. If the change of the carbon source lasts for a long time, a shift in the proportion of the several groups can occur, which means that a new steady state has then to be established.

The sudden occurrence of high concentration of xenobiotics, heavy metals, detergents, oxygen, etc. is very common in treatment plants. Their effects depend on the severity (duration and concentration) of the event, but these compounds can also inhibit the methanogens, and cause consequent accumulation of VFA and a drop in pH. In the case of oxygen, the facultative bacteria present in the granules can use the compound before it can affect the methanogens.

To overcome the problems related to operational and environmental variations, several researchers have been working on innovative procedures for monitoring, modelling and controlling the anaerobic reactors. The main objectives of these works are the same: to improve the stability and reliability, or robustness of the AnWT. Models not only aim to the design, operation and optimisation of treatment systems, but also to validate experimental data (or vice versa) and help the comparison between different systems.

Despite all of the aforementioned studies, there still remain some unclear aspects which could improve the stability and reliability of the anaerobic processes, or at least exonerate the prejudices. For instance, in the case of sewage treatment using UASB reactors, the applicable hydraulic retention times are still a subject of controversy. Moreover, the use of this system for the treatment of sewage with relatively low or high COD concentrations, i.e. around 200mgCOD/L or around 1500mgCOD/L, is still undergoing trials. This is because the knowledge on the performance of UASB reactors on the treatment of municipal wastewater in extreme situations is quite limited. However, the same is true for all conventional wastewater treatment systems; both high and low rate systems.

A lack of information also exists on the dynamics of the sludge in UASB reactors. During a hydraulic or organic shock load, the sludge bed will expand. Therefore, it is important to assess the relationship between the shock strength and the sludge bed expansion phenomenon, as well as the effects of several other operational parameters on the dynamic behaviour of the sludge bed.

Finally, since there still are engineers and researchers postulating that UASB reactors would be unable to accommodate high variations in organic or hydraulic load, a well organised set of experiments is needed to assess the limit of the UASB reactors with respect to shock loads. This appears to be the only comprehensible method to eliminate these prejudices.

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6

PERFORMANCE OF UASB REACTORS TREATING MUNICIPAL WASTEWATER UNDER HYDRAULIC AND ORGANIC SHOCK LOADS

One of the concerns on the use of Upflow Sludge Blanket (UASB) reactors for the treatment of sewage is the lack of knowledge about their capacity to withstand severe operational variations. In the present investigation, the robustness and stability of UASB reactors was evaluated on the basis of four indicators: (i) COD removal efficiency, (ii) effluent variability, (iii) pH stability, and (iv) recovery time. The experimental investigation was carried out using a set of six pilot-scale UASB reactors fed with domestic sewage and operated under different operational conditions. After establishment of a "steady state", organic shock loads were imposed by increasing the influent concentration approximately five times during a six-hours period. Next, hydraulic shock loads were imposed by increasing the flow rate three times during a six-hour period. The results show that the UASB reactors are robust systems with regards to COD removal efficiency and pH stability when exposed to shock loads. However, this reactor cannot attenuate the imposed fluctuation in the influent COD. Either a secondary treatment unit is needed to retain the expelled sludge occurring as a result of a hydraulic shock load, or prior to the shock, a sufficient amount of sludge needs to be discharged from the reactor.

6.1. INTRODUCTION

Although anaerobic wastewater treatment (AnWT) systems have already been applied successfully under different operational (organic and hydraulic loading rate) and environmental conditions (van Haandel and Lettinga, 1994; Vieira *et al.*, 1994; Schellinkhout and Collazos, 1992; and Haskoning *et al.*, 1985), a number of critical questions still remain. One of the bottlenecks is the lack of knowledge about the capacity of high rate anaerobic systems, such as Anaerobic Upflow Sludge Blanket (UASB) reactors, to cope with severe environmental and operational variations. This may cause serious problems of reliability and has led to a certain prejudice against the use of these systems for the treatment of municipal sewage. In case of sewage, the cyclical nature of human activities leads to a variable production over the day (Campos and von Sperling, 1996; Butler *et al.*, 1995; and Metcalf & Eddy, 1991). Moreover, inappropriate connections of runoff water and rainfall, variation of the population in tourist areas, as well as operational procedures at the sewerage and treatment plant, can result in increasing hydraulic and organic loads (Orhon *et al.*, 1999; Puñal and Lema, 1999; Dauphin *et al.*, 1998; and Castillo *et al.*, 1997).

In general, it can be said that AnWT systems behave in a similar manner when they are exposed to an abrupt increase of the hydraulic or organic loading rate, or less favourable environmental conditions. The typical response may be an incomplete methanogenesis, resulting in accumulation of volatile fatty acids – VFA (mainly propionate and butyrate), a drop in pH and bicarbonate alkalinity, a lower biogas production and changing in composition, i.e. an increase on the CO_2 and H_2 gas content, and sometimes in a temporary higher sludge washout (van Lier *et al.*, 2001; Chua *et al.*, 1997; Fongastitkul *et al.*, 1994; Cánovas-Díaz and Howell, 1988; Eng *et al.*, 1986; and Cohen *et al.*, 1982). Consequently, strong variations in flow and concentration may detrimentally affect the average efficiency of UASB reactors. The extent of these harmful effects obviously depends on the characteristics of the treatment system (reactor configuration, ratio organic load and organic load potential, and availability of a fault detection and control system), and also on factors related to the variation itself, such as type of the imposed shock loads, its extent, frequency and duration (Huang *et al.*, 2000; El Farhan and Shieh, 1999; Nachaiyasit and Stuckey, 1997a; b; and Xing *et al.*, 1997).

The present study evaluated the effects of drastic variations in the influent COD (COD_{Inf}) and hydraulic retention time (HRT) on the robustness of UASB reactors treating domestic sewage. This robustness was evaluated based upon (i) the capacity of the reactors to retain the imposed shock load (COD removal efficiency), (ii) the extent in which the quality of the effluent is affected by a shock load (effluent variability), (iii) the pH and bicarbonate stability during shock loads; and (iv) the time necessary for the reactor to recover from the shock loads (recovery time). Organic and hydraulic shock loads were imposed to six pilot-scale UASB reactors which had been operated under "steady state" conditions; each reactor at a different set of HRT and COD_{Inf}.

6.2. MATERIAL AND METHODS

6.2.1. Experimental Set-Up

The experimental investigation was carried out using six out of the 11 pilot-scale UASB reactors described in Chapter 2. Briefly, these reactors had a volume of 120 litres and were fed with domestic sewage at a temperature of around 27°C. The reactors were denominated by $R^{HRT}{}_{COD}$, where the superscript index stands for the hydraulic retention time, and the subscript index for the total influent COD, both values representing the average during the "steady state" operational conditions.

6.2.2. Operation of the UASB Reactors During Shock Loads

Firstly, organic shock loads were imposed to the reactors, and approximately one month later, hydraulic shocks were imposed. Table 6.1 presents the operational procedure during the shock loads.

Table 6.1 – Operational parameters during steady state and shock conditions.

		Set 1				Set 2		
	Reactors	$R^6{}_{816}$	$R^6{}_{555}$	$R^6{}_{298}$	$R^6{}_{195}$	$R^6{}_{816}$	$R^4{}_{770}$	$R^2{}_{787}$
HRT	"Steady State"	6.0	6.0	6.0	6.0	6.0	4.0	2.0
	Organic Shock	6.0	6.0	6.0	6.0	6.0	4.0	2.0
	Hydraulic Shock	2.0	2.0	2.0	2.0	2.0	1.3	0.7
V_{up}	"Steady State"	0.64	0.64	0.64	0.64	0.64	0.95	1.90
	Organic Shock	0.64	0.64	0.64	0.64	0.64	0.95	1.90
	Hydraulic Shock	1.92	1.92	1.92	1.92	1.92	2.85	5.70
COD_{Inf}	"Steady State"	816	555	298	195	816	770	787
	Organic Shock	4112	2969	1667	933	4112	3424	3581
	Hydraulic Shock	816	555	298	195	816	770	787
OLR	"Steady State"	3.3	2.2	1.2	0.8	3.3	4.6	9.4
	Organic Shock	16.4	11.9	6.7	3.7	16.4	20.5	43.0
	Hydraulic Shock	9.8	6.7	3.6	2.3	9.8	13.9	28.3

HRT (hours), V_{up} (m/h), COD_{Inf} (mgCOD/L), OLR (kgCOD/m^3.day). Reactor $R_6{}^{816}$ is repeated to create the two sets above.

Organic shock loads were carried out by increasing the influent concentration approximately five times during a period of six hours, while maintaining a constant HRT. Hydraulic shock loads were performed by increasing the flow rate three times for a period of six hours, while maintaining an almost constant influent COD concentration. These procedures imply that the organic loading rates (OLRs) were also increased five and three times during the organic and hydraulic shock loads respectively.

All shock loadings started at 10:00am and terminated at 04:00pm. A 72-hours intensive monitoring campaign was carried out, comprised of the following measurements: the determination of sludge bed profile, and of the influent and effluent characteristics were conducted 24 hours before starting the shock loadings; during the day of the shock load (starting always at 8:00 am) the influent and effluent were sampled hourly for to determine COD concentration (total, settled, suspended and dissolved), pH, VFA concentration, bicarbonate alkalinity, total solids and volatile solids; gas production and gas composition (CH_4 and CO_2) were monitored hourly as well. Effluent samples were taken from a storage tank with a capacity of one hour. The hourly monitoring campaign was finished 24 hours after the shock load started. However, final determinations for sludge bed profile, and influent and for effluent characterisation were conducted 48 hours after the shock started. Methane production was determined in one 24-hour monitoring campaign some days before the shock load experiments (representing the "steady state" condition), and during the shock load. Methane production was assessed using a Mariotte bottle with 120L of volume, filled with a solution of NaOH (5%w/w).

6.2.3. Influent

The Influent During Steady State Conditions

The characteristics of the influent, comprising the sewage of Campina Grande city - Brazil (350,000 inhabitants), during the "steady state" conditions, have already been described in Chapter 2. The wastewater was screened before use, and stored in a tank with a capacity of 24 hours. Reactors R^6_{555}, R^6_{298} and R^6_{195} were operated with sewage which was diluted using tap water. The main characteristics of the feed of the reactors prior to the shock loads experiments are summarised in Table 6.2.

Evaluation of the Influent Fluctuation

Seven monitoring campaigns were performed to evaluate the COD fluctuation of the sewage in Campina Grande (one on each day of the week). The campaigns consisted of sampling the raw sewage hourly, starting at 0:00h and finishing at 24:00h. The sewage samples were withdrawn from the interceptor sewer of the city. Each sample was analysed separately (no composite sample).

Table 6.2 – Characterisation of the influent used during steady state conditions.

Parameter	Reactors					
	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^4_{770}	R^2_{787}
Total COD (mg/L)	816	555	298	195	770	787
Suspended COD (mg/L)	566	421	216	120	459	513
Dissolved COD (mg/L)	250	134	82	75	312	274
Total VFA (mg/L)	180	88	42	28	164	164
Alkalinity (mg$CaCO_3$/L)	373	255	164	134	336	358
pH	7.3	7.4	7.5	7.3	7.6	7.6
Total Solids (mg/L)	1249	926	803	626	1037	1107
Volatile Solids (mg/L)	581	354	308	205	455	440

<u>The Influent During Shock Loads Conditions</u>

For the organic shock loads, the feed concentration was enhanced by a mixture of vinasses and primary sludge, according to the scheme in Table 6.3. The hydraulic shocks were imposed without altering the sewage characteristics.

Table 6.3 – Characterisation of the mixture used during the organic shock load conditions. In brackets the ratio between shock load and "steady state" values.

Parameter	Reactors					
	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^4_{770}	R^2_{787}
Total COD (mg/L)	4112 (5.0)	2969 (5.3)	1667 (5.6)	933 (4.8)	3424 (4.4)	3581 (4.6)
Suspended COD (mg/L)	1011 (1.8)	758 (1.8)	822 (3.8)	244 (2.0)	1404 (3.1)	1257 (2.5)
Dissolved COD (mg/L)	3101 (12.4)	2211 (16.5)	845 (10.3)	689 (9.2)	2020 (6.5)	2324 (8.5)
Total VFA (mg/L)	462 (2.8)	1069 (12.1)	357 (8.5)	236 (8.4)	776 (4.7)	658 (4.0)
Alkalinity (mg$CaCO_3$/L)	50	778	187	192	459	564
pH	4.3	6.6	6.1	6.6	6.1	6.7
Total Solids (mg/L)	3065	3229	1655	1030	3040	2684
Volatile Solids (mg/L)	1861	1731	913	487	1838	1311

During the organic shock load, the ratio between the total influent COD during shock and total influent COD during "steady state" was approximately 5. However, it was not possible to produce a mixture with the same ratio neither for either the dissolved and suspended fraction, or the VFA concentration. The values for these ratios are presented in brackets in Table 6.3.

6.2.4. Analytical Methods

All physical-chemical analyses were according to APHA (1995). Raw samples were used for Total COD; filtered samples for paper filtered COD were performed using 4.4μm folded paper filters (Schleicher & Schuell 595½, Germany); and using 0.45 μm membrane filters (Schleicher & Schuell ME 25, Germany) for dissolved COD. The micro-COD method was used for all COD analysis. Total VFA was determined following the procedure described in (Buchauer, 1998).

The suspended solids fraction and dissolved fraction of the influent and effluent (expressed as COD) were calculated using equations described in Chapter 2.

6.2.5. Indicators Used for Evaluating the Robustness of the Reactors Under Shock Loads

Four indicators were defined to evaluate the "robustness" of the reactors when exposed to shock loads. These indicators were conceived to enable a comparison among the different operational conditions imposed to the UASB reactors, and quantitatively show their robustness during transient conditions.

COD Removal Efficiency

The ability of the system to retain shock loads can ultimately be used to evaluate whether the overload will affect the next unit of the wastewater treatment plant, and/or whether the treated wastewater will still comply with the legislation for discharge during the transient condition.

Parameters used in this chapter are similar to those in Chapter 2 ("steady state" operation). The COD removal efficiency was calculated based on values of total effluent/total influent COD concentrations (E_{Tot}), settled effluent/total influent COD concentrations (E_{Set}) (1 hour of settling time), dissolved effluent/dissolved influent (E_{Dis}), effluent VFA/influent VFA (E_{VFA}), and non-acidified dissolved effluent COD/non-acidified dissolved influent COD (E_{NAc}). For the assessment of SS removal efficiency, all effluent suspended solids that settled after one hour represent excess sludge, while the non-settleable suspended COD fraction in the effluent accounts for the calculation of the SS removal efficiency (E_{SS}^{Set}). All COD removal efficiencies were calculated using Equation 6.1.

During the shock load experiments, the COD removal efficiencies were calculated based on the mass of the COD imposed to the system during the period of 24 hours (starting from the beginning of the shock), and mass of COD in the effluent during the same period (Equations 6.2 to 6.7). The results provide the 24-hour-average COD removal efficiencies. This approach was necessary because the effluent concentrations change with a certain delay to changes in influent concentrations.

$$E = \left(1 - S_{Eff} / S_{Inf}\right) \times 100 \quad \text{(Eq. 6.1)}$$

$$S = \sum_{i=0}^{i=24} COD_i \times Q_i \times \Delta t_i \quad \text{(Eq. 6.2)}$$

Where: E is the COD removal efficiency (%), COD_i is the concentration (gCOD/L) in a specific hour "t" during the transient condition, S is the mass of COD (g) imposed during the 24 hours after the shock started, and Q_i (L/h) is the flow rate at this time and Δt_i (h) is the interval between measurements.

$$S_{Inf}^{Tot} = S_{Inf}^{SS} + S_{Inf}^{Dis} \quad \text{(Eq. 6.3)}$$

$$S_{Inf}^{Dis} = S_{Inf}^{VFA} + S_{Inf}^{NAc} \quad \text{(Eq. 6.4)}$$

$$S_{Eff}^{Tot} = S_{Eff}^{Set} + S_{Eff}^{X} \quad \text{(Eq. 6.5)}$$

$$S_{Eff}^{Set} = S_{Eff}^{SS} + S_{Eff}^{Dis} \quad \text{(Eq. 6.6)}$$

$$S_{Eff}^{Dis} = S_{Eff}^{VFA} + S_{Eff}^{NAc} \quad \text{(Eq. 6.7)}$$

Where the indexes "Inf" and "Eff" stands for influent and effluent respectively. The indexes "Tot" stands for Total Influent, "SS" for suspended solids fraction, "Dis" for dissolved fraction, VFA for the volatile fatty acids as COD, "NAc" for the non-acidified dissolved fraction, "Set" for the settled effluent COD, "X" for the excess sludge as COD. All values of "S" are in grams of COD.

Effluent Variability

During "steady state" conditions, the performance of the reactors was also evaluated on the basis of the settled effluent variability, which is the ratio between the standard deviation and the average of the settled effluent COD (both standard deviation and average were calculated using data of the whole "steady state" operational period). This parameter gives insight into the fluctuation in effluent quality, which is inherent to these kinds of reactor, and into the reactors' capacity to attenuate the imposed fluctuation in influent concentration.

To evaluate the extent of the effluent fluctuation during transient conditions, the highest value of the six-hour moving average of the effluent COD was used, rather than the standard deviation for the calculation of the effluent variability. This is because it was necessary to assess the variability relative to the "steady state" average. However, the standard deviation stands for the dispersion of the values in relation to the average of a set of data, and during shock loads the average effluent COD (the set of data) is higher. Thus, the effluent variability during the shock loads is the maximum value for the ratio between the six-hour moving average and the "steady state" average of the settled effluent COD.

pH Stability

Following the same evaluation made for reactors under "steady state" operational conditions, the stability of the UASB reactors under shock load conditions was evaluated in terms of total and bicarbonate alkalinity, pH, total VFA concentration, and VFA/Alkalinity (bicarbonate) ratio. The VFA/Alkalinity ratio was suggested by Behling *et al.* (1997); Fongastitkul *et al.* (1994); and Ripley *et al.* (1986) as a good indicator of the pH stability of the reactor. According to these researchers, a value exceeding 0.4 for this ratio might indicate that the anaerobic reactor becomes unstable.

Recovery Time

One of the main concerns about the use of UASB reactors is their presumed long period of recovery time after an abrupt change in operational or environmental conditions. This is mainly due to the slow-growing methanogenic bacteria (Bhatia *et al.*, 1985; de Zeeuw, 1984; and Lettinga *et al.*, 1980), which usually limits the process performance in these cases.

In this study, the indicator "recovery time" is defined as the time required (starting from the beginning of the shock) for the settled effluent COD values to return to the average values found under "steady state" conditions. For this purpose, the settled effluent was chosen as the indicator of the recuperation, because in most cases, this is the last parameter to reach the "steady state" values.

It should be noted that during "steady state" conditions, the settled effluent COD concentration of all reactors fluctuated within a certain range. This range was calculated using the standard deviation. Consequently, the "recovery time" stands for the period between the start of the imposed shock load and the instant when the values of settled effluent COD reached the aforementioned range (or the "steady state" values).

6.3. RESULTS AND DISCUSSION

6.3.1. The Organic Shock Load Experiments

6.3.1.1. The Results of the Organic Shock Loads

The results of the seven monitoring campaigns for the characterization of the sewage of Campina Grande, depicted in Figure 6.1, reveal that an increase of up to 100% in the sewage COD concentration is very common. Occasionally, the sewage COD concentration even increased 5-fold, mainly during a period of water shortage (results not presented here). Based on the results of the monitoring campaigns and on the information obtained during the span of the research, it was considered that a shock load of five times the average influent COD concentration, with a duration of 6 hours, would represent a good simulation of an extreme situation that can occur in practice.

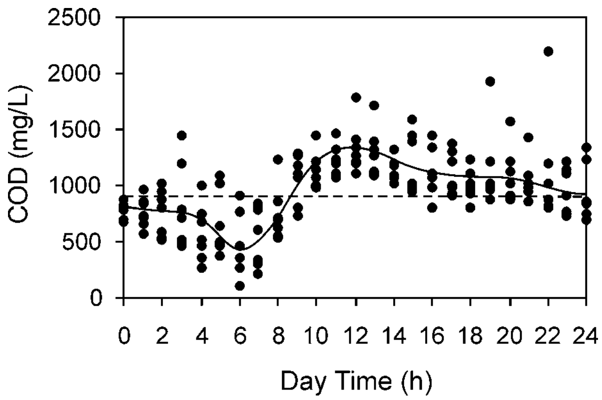

Figure 6.1 – Results of seven monitoring campaigns surveying the sewage COD concentration of Campina Grande. Continuous line represents the the average at each hour of the day. Dashed line represents the overall average.

The results of the organic shocks loads are depicted in Figures 6.2 and 6.3, where the response of the reactors is shown in terms of effluent COD (total, settled, as well as suspended and dissolved fractions), sludge washout, gas production, and effluent VFA and total alkalinity. To limit the number of graphs, Figure 6.2 only shows the results of the reactors operated with the highest and the lowest COD_{Inf} (R^6_{816} and Reactor R^6_{195}). Similarly, only the results of reactors operated at the longest and the shortest HRT are shown in Figure 6.3, respectively R^6_{816} and R^2_{787}. The trends observed in the other reactors (R^6_{555}, R^6_{298} and R^4_{770}) were similar.

After the start of the organic shock load, the total effluent COD increased up to values 12 times higher than those usually found during the “steady state” operation. The total effluent COD is composed of settled effluent COD and sludge washout, both of which are discussed in the following sub-sections.

6.3.1.2. Settled Effluent COD During Organic Shock Load

The settled effluent COD increased steadily, and did not show any indication that the concentration would drop before the termination of the shock. The increased SS concentration in the effluent coincided with an elevated gas production, which might be the main reason for this phenomenon. It should be taken into account that a higher influent SS concentration was applied during the shock loads as a result of the addition of primary sludge consisting of relatively well settleable matter. As a result, part of the non-entrapped SS may have ended up as excess sludge instead of effluent SS (non-settleable fraction). Although the effluent SS concentration also increased over in time, the deterioration of the settled effluent quality can be mainly attributed to an increased dissolved COD. During the transient condition, around 80-90% of the settled effluent COD consisted of dissolved COD, whilst during “steady state”, this fraction ranged from 20-60%.

The dissolved effluent COD increased steadily after the shock load started, and took a long time to return to the previous values (up to 24 hours after the shock started). The effects of the organic shock loads on the acidified (VFA) and non-acidified fraction of the effluent dissolved COD are discussed below.

Similar to soluble COD, the effluent VFA of all reactors increased substantially as a result of the overload. During the organic shock loads however, the methanogenic potential of the reactor still enabled the system to convert considerable part of the supplied and produced VFA into methane, even though a 6-hour shock load only will result in the growth of a small amount of methanogenic bacteria.

The values calculated for the Maximum Methanogenic Potential (MMP) and “extra” VFA loading capacity are shown in Table 6.4 (see discussion about these parameters in Chapter 3). Table 6.4 also shows the VFA loading rate during shock loading conditions. The difference between the VLR during the shock load and MMP represents the VFA overload.

During the organic shock load, the acidogenesis rate may have increased, resulting in a higher conversion of the “extra” non-acidified influent COD to VFA. However, it was not possible to accurately assess the acidification rate during the period of the shock load. For the calculation of the VFA produced in the acidogenic step, it was assumed that the acidification rate increased during the shock loads and attained its maximum rate within the 6-hours period. The maximum VFA concentration was calculated based on the depletion of the non-acidified dissolved COD fraction (Equation 6.8).

The organic shock loads imposed to reactors R^6_{298} and R^6_{195} (operated with low COD_{Inf}) barely exceeded their capacity to convert the overcharge of VFA. The overload imposed to reactor R^6_{195} was approximately the same as the OLR applied to reactor R^6_{816} during “steady state”. Thus, it can be expected that reactor R^6_{195} would adapt relatively easily to a 5-fold step-change in the OLR, as far as the SS fraction in the influent is within the same ratio range.

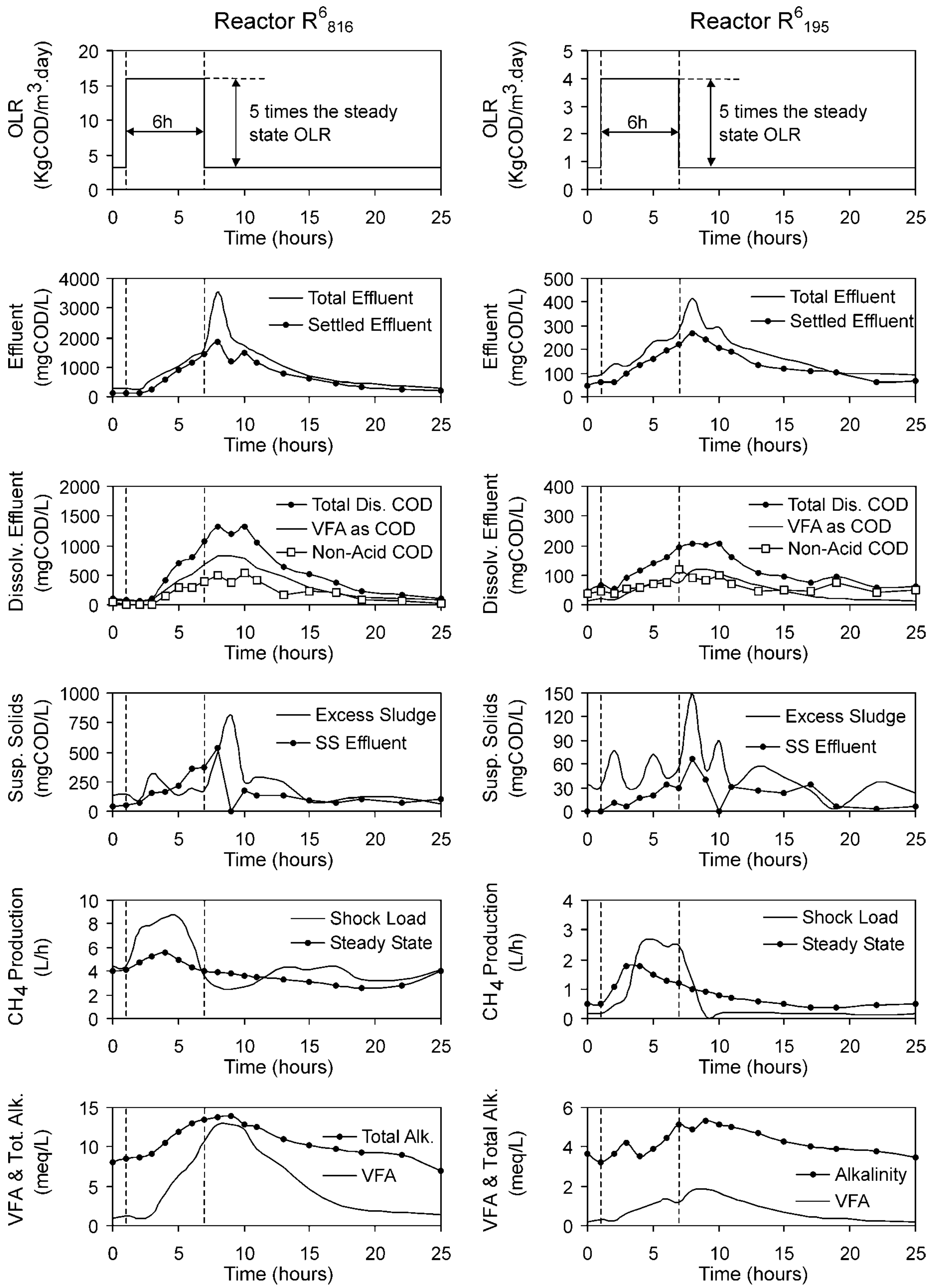

Figure 6.2 – Effect of **organic** shock load on the performance of UASB reactors operated with the same HRT (6h), but with different influent COD concentrations. Left column refers to Reactor R^6_{816}. Right column refers to Reactor R^6_{195}.

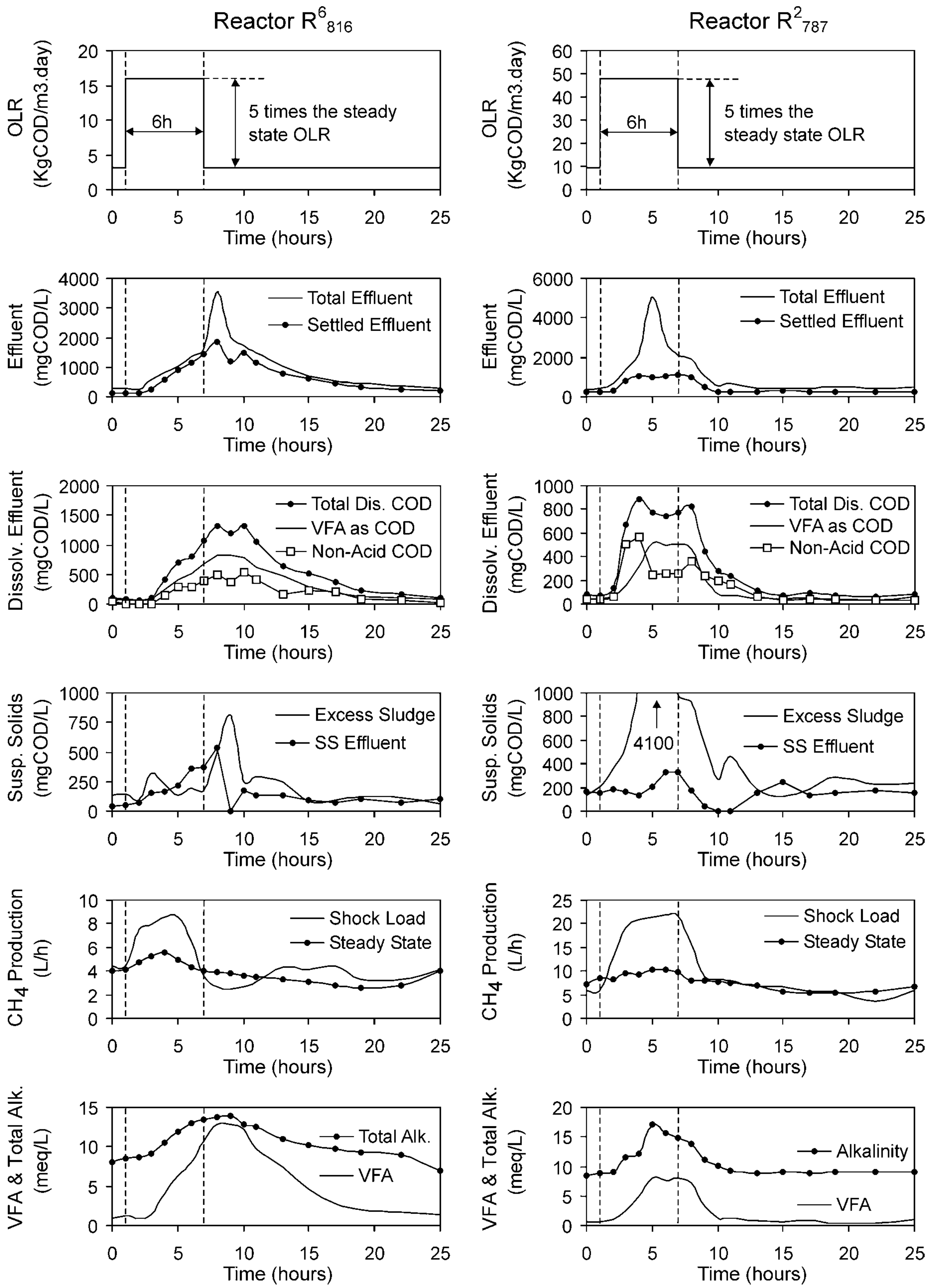

Figure 6.3 – Effect of **organic** shock load on the performance of UASB reactors operated with approximately the same COD_{Inf} (~800mg/L), but with different HRTs. Left column refers to Reactor R^6_{816}. Right column refers to Reactor R^2_{787}.

Table 6.4 – Maximum Methanogenic Potential (MMP) and VFA Loading Rate (VLR) during "steady state" and **organic** shock load.

Parameter (gCOD/h)	Reactors					
	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^4_{770}	R^2_{787}
Max Methan. Potent. (MMP)	15.8	15.4	12.5	11.1	28.6	57.3
Extra VFA loading capacity	5.3	7.9	7.9	8.7	16.7	36.1
VLR during Organic Shock	54.4	38.3	13.6	11.4	55.3	123.9
VFA Overload (Organic Shock)	38.6	22.9	1.1	0.3	26.7	66.6
Ratio VLR_{Shock}/MMP	3.4	2.5	1.1	1.0	1.9	2.2

$$COD_{Prod}^{VFA} = COD_{Inf}^{NAc} - COD_{Eff}^{NAc} \quad \text{(Eq. 6.8)}$$

Where: COD_{Prod}^{VFA} is the VFA produced during the acidogenic step, COD_{Inf}^{NAc} and COD_{Eff}^{Nac} are the non-acidified dissolved fraction in the influent and effluent respectively. The COD is given in (g/L).

The imposed overload of VFA affected the gas production of all reactors. The methane production rate increased due to the increased OLR during the organic shock loads. However, the reactors operated at influent concentrations higher than 500mgCOD/L showed some indication of the inhibition of methanogenesis. In these cases, the gas production rate reached a maximum level before termination of shock and then decreased (see the example of reactor R^6_{816} in Figure 6.2), although a significant amount of substrate from the shock was still present in the system. The acidification step proceeded well (although apparently not completely), but the methanogenic capacity of the system did not suffice to cope with that, and the methane production rate dropped despite the available high amounts of VFA. Inanc *et al.*, 1999 made a similar observation, i.e., high VFA concentration causes an inhibition of the methanogenesis.

The mixture used to impose the shock loads contained a high fraction of non-acidified COD, which should have overloaded the acidogenic step. This may explain the increasing values of non-acidified COD during the period of overloading.

6.3.1.3. Sludge Washout During Organic Shock Load

Sludge washout increased as a result of the shock load, always reached a peak and then declined. It is not clear whether this peak would become even higher if the shock would have continued for a longer time, as in some cases, for example in Reactor R^2_{787}, this peak was reached before termination of the shock load.

The peak of sludge washout can mainly be attributed to the expansion of the sludge bed, likely due to the higher gas production during the increased OLR. The reactors were operated under "steady state" at their maximum sludge accumulation conditions, and an increase of the gas production led to a new equilibrium situation in the sludge bed height, and consequently sludge expulsion occurred. Reactors operated during "steady state" at a higher COD_{Inf} resulted in a higher amount of sludge washout during organic shock loads. This may be due to the high gas production of reactors operated with concentrated wastewater. Since the sludge content of reactors is higher when operated with more concentrated wastewater, in these cases the amount of expelled sludge is also higher.

6.3.1.4. Indicators of the Robustness of the Reactors Under Organic Shock Loads

Values for the indicators of the robustness of the UASB reactors under organic shock loads conditions are summarised in Table 6.5.

<u>COD Removal Efficiency</u>

The COD removal efficiency represents the practical indicator, as it is broadly used in the wastewater treatment plants for evaluating the performance of the reactors (generally on the basis of 24-hour composite samples). However, this indicator partially hides the short-term fluctuations that occur in the influent or effluent.

In general, the reactors operated with a lower influent concentration or a shorter HRT perform better in terms of COD removal efficiencies based on settled effluent (E_{Set}). This could be the result of their higher capacity to cope with shock loads (the "extra" loading capacity), as can be deduced from the data in Table 6.4. However, considering the total COD removal efficiency (E_{Tot}), the high sludge washout of reactors operated at HRTs of 4 and 2 hours caused the deterioration of the total effluent quality. The negative removal observed for VFA in some of the reactors clearly illustrates that these systems were overloaded.

Table 6.5 – Performance of the different UASB reactors under **organic** shock load.

		Set 1				Set 2		
	Reactors	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^6_{816}	R^4_{770}	R^2_{787}
Influent COD	S_{Inf}^{Tot}	791	579	318	210	791	973	2147
	S_{Inf}^{SS}	286	256	178	88	286	451	993
	S_{Inf}^{Dis}	505	333	140	122	505	522	1154
	S_{Inf}^{VFA}	121	184	70	51	121	268	489
	S_{Inf}^{NAc}	384	149	70	71	384	254	665
Effluent COD	S_{Eff}^{Tot}	409	231	100	84	409	469	1491
	S_{Eff}^{Set}	316	196	80	62	316	278	649
	S_{Eff}^{SS}	70	32	20	9	70	127	236
	S_{Eff}^{Dis}	246	164	60	53	246	151	413
	S_{Eff}^{VFA}	156	87	31	24	156	120	210
	S_{Eff}^{NAc}	90	77	29	29	90	31	203
	S_{Eff}^{X}	93(71)	35(43)	20(13)	22(13)	93(71)	191(145)	842(287)
COD Removal Efficiency	E_{Tot}	48%	60%	69%	60%	48%	52%	31%
	E_{Set}	60%	66%	75%	70%	60%	71%	70%
	E_{SS}^{Set}	76%	88%	89%	90%	76%	72%	76%
	E_{Dis}	51%	51%	57%	57%	51%	71%	64%
	E_{VFA}	-29%	53%	56%	53%	-29%	55%	57%
	E_{NAc}	77%	48%	59%	59%	77%	88%	69%
Variability		807%	732%	522%	427%	807%	386%	437%
Recovery Time (h)		24	23	21	21	24	12	10
PH Stability	PH min	6.5	6.9	6.8	6.8	6.5	6.90	6.71
	Alk. min	4.1	5.6	3.4	2.9	4.1	5.7	8.0
	VFA max	12.9	7.8	2.5	1.9	12.9	6.9	8.1
	VFA/Alk max	2.1	0.7	0.6	0.5	2.1	0.7	0.8

The S values presented in this table refer to the total mass of COD (g) calculated for the period of 24 hours, starting from the beginning of the shock loads (Equations 6.2 – 6.7). Alkalinity in terms of bicarbonate (meq/L), and VFA refers to total VFA (meq/L). The indexes stand for: Inf – Influent; Eff – Effluent; Tot – Total; SS – Suspended solids fraction; Dis – Dissolved fraction; VFA – Volatile fatty acids; NAc – Non-acidified fraction; X – Excess sludge or sludge washout; Set – settled effluent. The values of sludge washout in brackets refer to the “steady state” condition, for a period of 24 hours, as a reference value. Reactor R^6_{816} is repeated to create the two sets above.

Effluent Variability and Recovery Time

The settled effluent COD varied in the range of 400-800% (relative to the “steady state” values of settled effluent COD) for all reactors operated under a shock load of five times the influent concentration. This is an indication that the UASB reactors cannot attenuate strong fluctuations in the influent concentration.

The “recovery time” of an organic shock load appears to be highly dependent on the HRT. Reactors operated with an HRT of 6 hours needed from 20-24 hours to recover the “steady state conditions, whilst reactors operated with shorter HRT (4 and 2 hours) needed 12 and 10 hours respectively to recover from the shock. It seems that the recovery time might have a strong relation to the dilution rate.

pH Stability During Organic Shock Loads

Effluent bicarbonate alkalinity was always relatively high due to the kind of mixture used to impose the organic shocks, and there was always some increase in buffering capacity when VFA was converted to methane.

However, Table 6.4 reveals that most of the reactors were seriously overloaded during the organic shock load, except perhaps reactors R^6_{298} and R^6_{195}. VFA concentration in the effluents of the reactors increased steadily during the shock load, showing that this raise would not stop if the shock would continued for a longer period. Obviously, there is a maximum to the amount of VFA that can be accumulated, comprising the situation when the acidification of the biodegradable influent substrate is complete and methanogenesis is totally inhibited. If the shock load continued, the accumulation of VFA in most of the reactors would cause the complete consumption of the bicarbonate alkalinity, and the system would become acidified. Therefore, there was a trend for the acidification of the reactor’s contents in almost all cases, reflected in the values of the ratio VFA/Alkalinity (Table 6.5) that became far beyond the risky level (0.4) during the transient conditions (Behling *et al.*, 1997; Fongastitkul *et al.*, 1994; and Ripley *et al.*, 1986).

6.3.1.5. Mass Balance for the Organic Shock Loads

Table 6.6 presents the mass balance for the period of 24 hours starting from the beginning of the organic shock loads. Since the input and output mass of COD deviate from each other (the COD recovery should be 100% based on Equation 6.9), it is clear that the mass balance does not close. This fact can be mainly due to errors during the measurements of the sludge mass in the reactor, which was assessed through the sludge profile, known to be rather inaccurate. Moreover, the conversion factor of sludge VS in COD was assumed to be 1.5gCOD/gVS, which can lead to miscalculations, as this ratio can vary with the biodegradability of the sludge. Other errors were also possible, for instance, the gas production was measured using a liquid displacement device which is sensitive to daily temperature changes.

Table 6.6 – Mass balance for the **organic** shock load.

	Set 1				Set 2		
Reactors	R^6_{816}(1)	R^6_{555}	R^6_{298}	R^6_{195}	R^6_{816}(1)	R^4_{770}	R^2_{787}
S_{Inf}^{Tot}	791	579	318	210	767	973	2147
S_{Eff}^{Set}	316	196	80	62	316	278	649
S_{Eff}^{X}	93	35	20	22	93	191	842
S_{CH4}	300	256	116	58	300	474	634
$\triangle M_X$	119	-76	170	101	119	327	-43
COD Recovery	105%	71%	121%	116%	105%	131%	97%

(1) Reactor R^6_{816} is repeated to create the two sets above.

$$\text{COD Recovery}(\%) = \left(\frac{S_{Eff}^{Set} + S_{Eff}^{X} + S_{CH4} + \Delta M_X}{S_{Inf}^{Tot}} \right) \times 100$$

(Eq. 6.9)

Where: S values refer to the total mass of COD (g) calculated for the period of 24 hours; the indexes Inf and Eff refer to influent and effluent respectively; the other indexes stand for: Tot – total, Set – settled effluent, X – excess sludge, CH4 – methane; $\triangle M_X$ refers to the difference between the mass of sludge in the reactor after and before the shock load ($\triangle M_X = M_{Xafter} – M_{Xbefore}$).

6.3.2. The Hydraulic Shock Load Experiments

6.3.2.1. The Results of the Hydraulic Shock Loads

Hydraulic shock loads were imposed to the various reactors by increasing the flow rate 3 times during a period of 6 hours, always by using the same influent. Such a situation may occur during few hours (peak flow period) in a case where one of the reactors of a two-module wastewater treatment plant is put out of operation for maintenance.

The results of the hydraulic shock loads are depicted in Figures 6.4 and 6.5, similarly to the description for the organic shock load experiments in Figure 6.2 and 6.3 (Section 6.3.2). Results are only shown for reactors operated with the highest and the lowest COD_{Inf}, and with the longest and the shortest HRT, as seen in Figures 6.4 and 6.5 respectively. The performance of all other reactors followed the same trend in performance as shown in these figures.

After the hydraulic shock load started, the total effluent COD immediately increased, and it reached a peak within the first two or three hours. This peak reached values up to 23 times higher than the values usually found during the "steady state" operation, and was mainly caused by a temporary sludge washout. However, in cases when the reactors were operated with low influent concentration, the settled effluent COD was the main cause for the deterioration of the reactor's performance after the shock ceased. Both parameters are discussed in the following sub-sections.

6.3.2.2. Settled effluent COD During Hydraulic Shock Load

The settled effluent COD showed a different picture for reactors operated with high and low influent concentrations. In the results of reactors operated with influent COD exceeding 500mg/L, a small peak manifested at the beginning of the shock load. This short-term deterioration (up to 8 hours after the shock started) was mainly due to the higher VFA concentration in the effluent. In reactors operated with lower influent concentrations (reactors R^6_{298} and R^6_{195}) such a peak did not manifest, but instead, the settled effluent COD concentration in these cases increased until the shock ceased (see graph of reactor R^6_{195} in Figure 6.4).

The medium-term effluent deterioration (up to 48 hours after the shock started) was mainly due to the SS fraction (non-settleable) in the settled effluent. Reactors operated at low influent concentrations resulted in an increased effluent SS when hydraulic shock loads were imposed, mainly because the sludges of these reactors are highly expansible (see Chapter 4). This expansion of the sludge bed caused a higher porosity (sludge voidage; see Chapter 4) that probably deteriorated the SS entrapment capacity. However, it is not clear why this detrimental effect took more than 48 hours to dissipate.

The non-acidified effluent COD remained almost unchanged during the hydraulic shock load, relative to the "steady state" situation. The increase in the non-acidified fraction shown for R^6_{195} in Figure 6.4 is still within the range during "steady state".

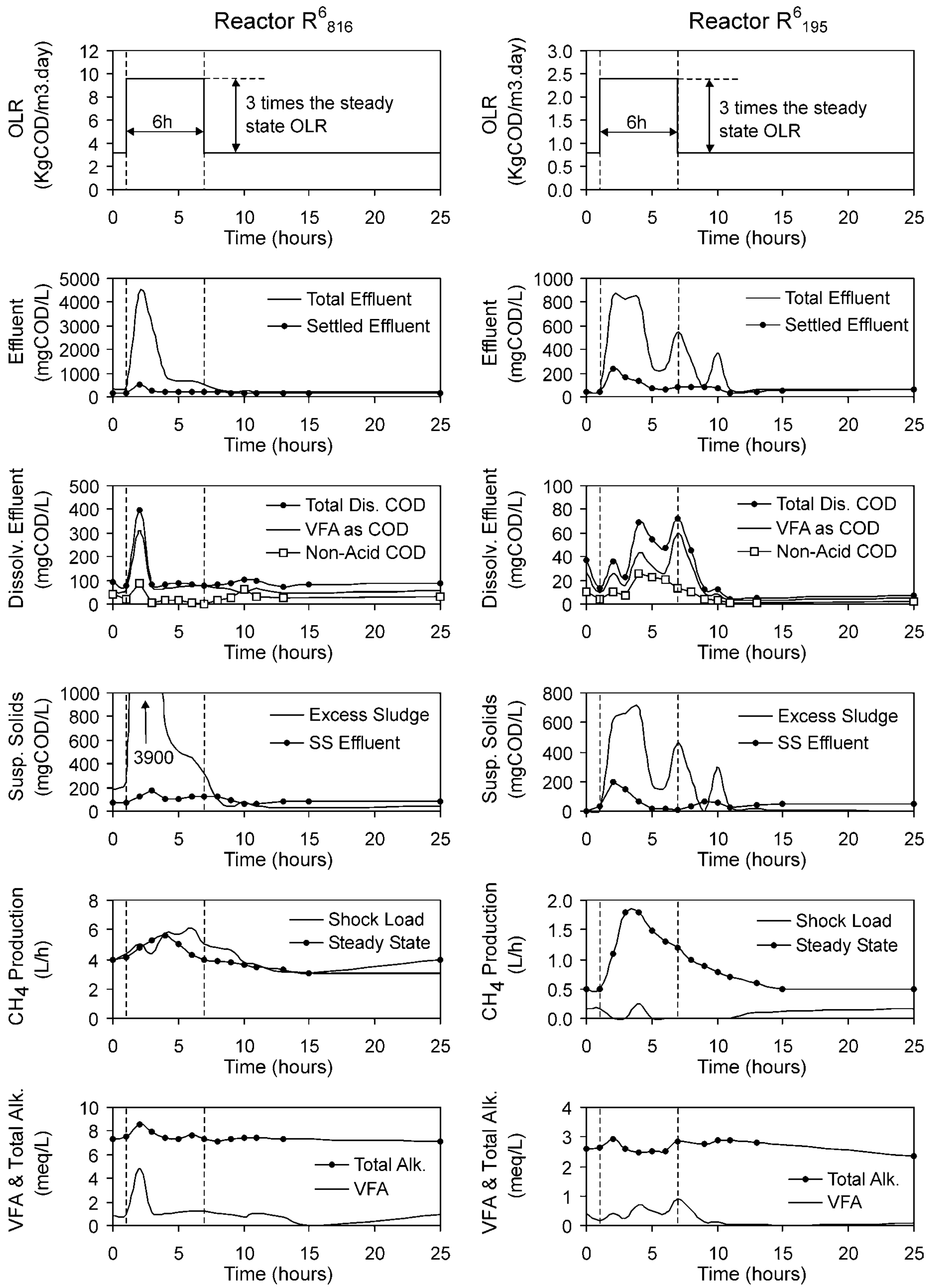

Figure 6.4 – Effect of **hydraulic** shock load on the performance of UASB reactors operated with the same HRT (6h), but with different influent COD concentrations. Left column refers to Reactor R^6_{816}. Right column refers to Reactor R^6_{195}.

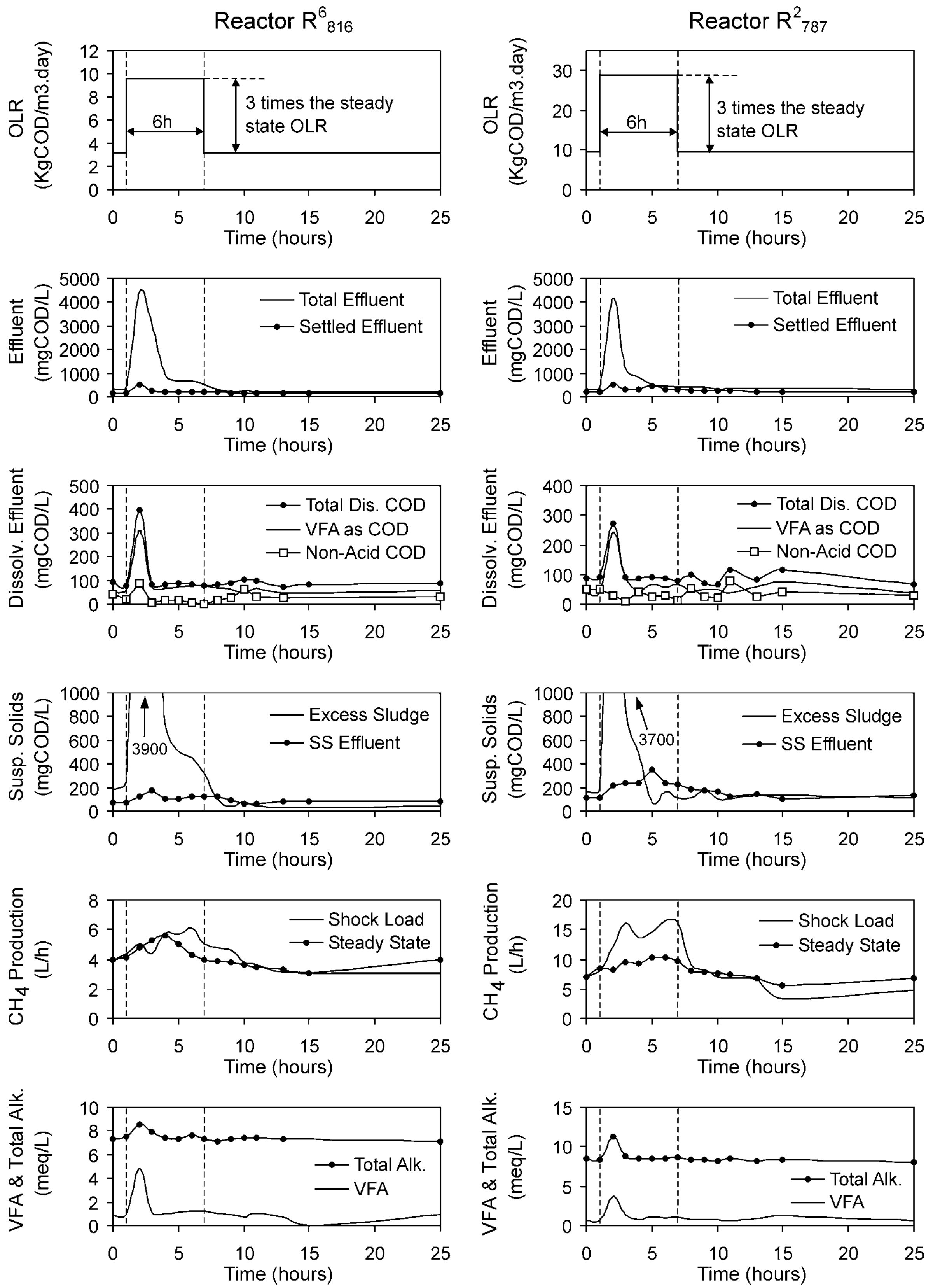

Figure 6.5 – Effect of **hydraulic** shock load on the performance of UASB reactors operated with approximately the same COD_{Inf} (~800mg/L), but with different HRTs. Left column refers to Reactor R^6_{816}. Right column refers to Reactor R^2_{787}.

Effluent VFA During Hydraulic Shock Load

The results presented in Table 6.7 show that the hydraulic shock loads imposed to the reactors did not lead to serious overloading. Nevertheless, the reactors operated with a high influent COD resulted in a sudden increase at the beginning of the shock load. The cause of this peak is not clear, but it seems that the reactors have a certain lag-phase before responding to a shock load of VFA.

The results of reactors operated with a low influent COD show a steady increase of the effluent VFA concentration until the shock ceased (see graph of reactor R^6_{195} in Figure 6.4). This may be because the oxygen content in the influent during the hydraulic shock causes the inhibition of the methanogenesis. The sludge of these reactors contained a certain amount of facultative bacteria that, when in "steady state" operation, rapidly consumed the dissolved oxygen present in the influent. This process proceeded within the bottommost 25 cm (as confirmed by oxygen concentration profile; results not shown), thus protecting the methanogenic bacteria (Kato, 1994). However, during an imposed hydraulic shock load (3 times higher flow rate), the amount of oxygen introduced to the system may have exceeded the capacity of the facultative bacteria. This inhibition is also reflected in the gas production.

Table 6.7 – Maximum Methanogenic Potential (MMP) and VFA Loading Rate (VLR) during "steady state" and **hydraulic** shock loads.

Parameter (gCOD/h)	Reactors					
	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^4_{770}	R^2_{787}
Max Methan. Potent. (MMP)	15.8	15.4	12.5	11.1	28.6	57.3
Extra VFA loading capacity	5.3	7.9	7.9	8.7	16.7	36.1
VLR during Hydraulic Shock	16.0	7.5	3.5	4.0	24.5	52.4
VFA Overload (Hydraulic Shock)	20.2	-7.9	-9	-7.1	-4.1	-4.9
Ratio VLR_{Shock}/MMP	1.0	0.5	0.3	0.4	0.9	0.9

* The negative sign means that the methanogenic step was not overloaded.

6.3.2.3. Sludge Washout During Hydraulic Shock Load

Sludge washout temporarily manifested in all reactors, i.e. mainly within the first two or three hours. In most cases, before the shock loads were terminated, the concentration of suspended solids in the effluent reached values just slightly higher than the "steady state" condition. A total recuperation of the reactors with regard to sludge washout occurred not more than 4 hours after the shock ceased.

In UASB reactors, hydraulic load variations affect the dynamics of the sludge bed (Rajesh *et al.*, 1999). The imposed hydraulic load fluctuations expand or shrink the sludge bed due to a new equilibrium among the upflow velocity, gas production and sludge settling velocity. Depending on the hydraulic load variation, a higher or lower settleable volatile solids concentration in the effluent is expected as a result of the washout of lighter biomass (O'Flaherty *et al.*, 1997; and Lettinga, 1995), the decreased filtration capacity of the sludge bed at higher upflow velocities (see Chapter 2), and the disintegration of granules or flocks under the abrasive action of shear forces (Chua *et al.*, 1997; and Kosaric *et al.*, 1990).

Obviously, the sludge washout during the hydraulic shock load increases as the HRT decreases. This is because the shock loads imposed to reactors which were operated at a low HRT were stronger than those imposed to reactors operated at a high HRT. For instance, the reactor operated with an HRT of 2 hours was submitted to V_{up} of 5.7m/h, while the reactors operated with HRT of 6 hours were submitted to V_{up} of 1.92m/h.

The expansibility of the sludge bed is highly dependent on way the system was operated under preceding "steady state" conditions, e.g. the sludge bed was found to be more expansible when the reactors were operated at a higher HRT and/or lower COD_{Inf} (see Chapter 4). However, the amount of sludge washed out from the system during a hydraulic shock load is not only a function of the expansibility of the sludge bed, but also the extent of the imposed shock load, the gas production during the shock and the concentration of the sludge in the sludge bed. Most of the sludge was expelled during the first 2 or 3 hours of shock, i.e. during the period when the sludge bed expanded to a new stabilised level.

The methodology for estimating the expansion of the sludge bed, discussed in Chapter 4, can be used to predict (approximately) the amount of sludge that will be expelled during the first hours of a hydraulic shock load. This estimation method takes into account merely the expansion due to the raise in the upflow velocity, and not the possible expansion due to the increased gas production. Moreover, increased gas production leads to more turbulence that may cause detachment of the entrapped solids (Mahmoud *et al.*, 2003). Figure 6.6 shows a comparison between the actual sludge washout during the first 2 hours of the hydraulic shock load and the calculated values for sludge washout using Equation 4.7 in Chapter 4. The 45-degrees line (dashed line) in Figure 6.6 represents the situation if the actual and calculated values for sludge washout were equivalents.

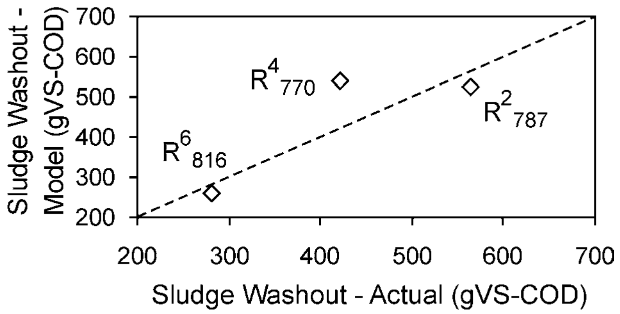

Figure 6.6 – Sludge Washout due to **hydraulic** shock loads: actual and calculated values. Labels near the data represent the reactors.

6.3.2.4. Indicators of Robustness of the Reactors Under Hydraulic Shock Loads

Values for the indicators of robustness of the UASB reactors under hydraulic shock loads conditions are summarised in Table 6.8.

COD Removal Efficiency

In general, the reactors operated with lower influent concentration resulted in low COD removal efficiency based on total effluent (E_{Tot}). This can be mainly attributed to the relatively high sludge washout during the hydraulic shock. Furthermore, the COD removal efficiency based on settled effluent (E_{Set}) of these reactors was also lower, which can be due to the lower SS entrapment capacity of the system and inhibition of methanogenesis.

Effluent Variability and Recovery Time

The settled effluent COD varied in the range of 120-240% (relative to the "steady state" values of settled effluent) for all reactors operated under a shock load of 3 times the flow rate applied during "steady state" conditions. The UASB reactors have some capacity to attenuate the fluctuation in OLR when the flow rate is increased. However, a secondary unit, e.g. a settler, needs to be installed in cases of reactors operated without sludge discharge – as was the case in our experiments – in order to cope with hydraulic shock loads; the total effluent varied up to 2300% during the hydraulic shock due to sludge washout.

The recovery time from a hydraulic shock load was always very short, viz. the values of settled effluent COD always returned to the "steady state" conditions within at most 3 hours after the termination of the shock load.

Table 6.8 – Performance of the different UASB reactors under **hydraulic** shock load.

		Set 1				Set 2		
	Reactors	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^6_{816}	R^4_{770}	R^2_{787}
Influent COD	S_{Inf}^{Tot}	571	396	216	146	571	934	1853
	S_{Inf}^{SS}	374	n.d.	n.d.	86	374	617	1182
	S_{Inf}^{Dis}	197	n.d.	n.d.	60	197	317	671
	S_{Inf}^{VFA}	115	61	26	18	115	234	487
	S_{Inf}^{NAc}	82	n.d.	n.d.	42	82	83	184
Effluent COD	S_{Eff}^{Tot}	720	552	356	248	720	1092	1753
	S_{Eff}^{Set}	161	82	46	67	161	241	625
	S_{Eff}^{SS}	75	n.d.	n.d.	47	75	122	422
	S_{Eff}^{Dis}	86	n.d.	n.d.	20	86	119	203
	S_{Eff}^{VFA}	65	23	13	15	65	79	142
	S_{Eff}^{NAc}	21	n.d.	n.d.	5	21	40	61
	S_{Eff}^{X}	559(71)	470(43)	310(13)	181(13)	559(71)	851(145)	1128(287)
COD Removal Efficiency	E_{Tot}	-26%	-39%	-65%	-70%	-26%	-17%	5%
	E_{Set}	72%	79%	79%	54%	72%	74%	66%
	E_{SS}^{Set}	80%	n.d.	n.d.	45%	80%	80%	64%
	E_{Dis}	56%	n.d.	n.d.	67%	56%	62%	70%
	E_{VFA}	43%	62%	50%	17%	43%	66%	71%
	E_{NAc}	74%	n.d.	n.d.	88%	74%	52%	67%
Variability		147%	117%	132%	246%	147%	117%	157%
Recovery Time (h)		3	4	5	9	3	2	8
PH Stability	PH min	6.9	7.0	7.0	6.8	6.9	7.3	7.4
	Alk min	6.3	3.5	2.3	1.9	6.3	6.9	7.5
	VFA max	4.8	1.8	0.4	0.9	4.8	5.1	3.8
	VFA/Alk max	0.8	0.4	0.2	0.3	0.8	0.6	0.4

The S values presented in this table refer to the total mass of COD (g) calculated for the period of 24 hours, starting from the beginning of the shock loads (Equations 6.2 – 6.7). Alkalinity in terms of bicarbonate (meq/L), and VFA refers to total VFA (meq/L). The indexes stand for: Inf – Influent; Eff – Effluent; Tot – Total; SS – Suspended solids fraction; Dis – Dissolved fraction; VFA – Volatile fatty acids; NAc – Non-acidified fraction; X – Excess sludge or sludge washout; Set – settled effluent. The values of sludge washout in brackets refer to the "steady state" condition, for a period of 24 hours, as a reference value. Reactor R^6_{816} is repeated to create the two sets above.

pH Stability During Hydraulic Shock Loads

The effluent bicarbonate alkalinity always remained relatively high and did not change significantly during or after the shock. The peak in VFA concentration that occurred in reactors operated with a high COD_{Inf} did not cause any detrimental effect on the pH stability of the reactors. However, the effect of a long-term hydraulic shock on reactors operated with low influent concentration is not clear, because the amount of dissolved oxygen imposed to the system may then have a detrimental effect. The worst scenario is the complete failure of the methanogenic step and a complete acidification of all biodegradable matter (the VFA reaches their maximum possible concentration when it exceeds the bicarbonate alkalinity). The best scenario would be that the methanogenesis resumes due to a new equilibrium between the methanogenic and facultative bacteria.

6.3.2.5. Mass Balance for the Hydraulic Shock Loads

The mass balance for the period of 24 hours starting from the beginning of the hydraulic shock load is presented in Table 6.9. An enormous discrepancy between the input and output mass of COD was found. The possible errors were mentioned previously. It is likely that the estimated sludge washout (based on the two sludge profiles made before and after the shock load) was the main cause of such an error.

Table 6.9 – Mass balance for the **hydraulic** shock load.

	Set 1				Set 2		
Reactors	R^6_{816}	R^6_{555}	R^6_{298}	R^6_{195}	R^6_{816}	R^4_{770}	R^2_{787}
S_{Inf}^{Tot}	571	396	216	146	571	934	1853
S_{Eff}^{Set}	161	82	46	67	161	241	625
S_{Eff}^{X}	559	470	310	181	559	851	1128
S_{CH4}	241	135	29	24	241	326	504
$\triangle M_X$	-179	-54	-27	-163	-179	-182	-611
COD Recovery	137%	160%	166%	75%	137%	132%	89%

Reactor R^6_{816} is repeated to create the two sets above.

6.4. CONCLUSIONS

Based on the results presented in this chapter, it can be concluded that:

(i) UASB reactors treating sewage under tropical conditions at HRT ranging from 2 to 6 hours, and OLR ranging from of 0.8 to 9.4 kgCOD/m3.day are ROBUST with regard to their ability to cope with a five-fold organic or a three-fold hydraulic shock loads, both with duration of 6 hours. Despite the strong shock loads, the UASB-reactor system can maintain roughly the same COD removal efficiency (based on 24-hours composite sample of the settled effluent) as found under "steady state" conditions.

(ii) The UASB reactors are ROBUST for withstanding the three-fold hydraulic shock loads with regard to pH stability when treating sewage in tropical countries. Even for reactors operated under extreme conditions, the pH, alkalinity or buffer capacity did not change significantly.

(iii) Although UASB reactors treating sewage can withstand a five-fold organic shock in terms of pH-stability and COD treatment efficiency, organic shock loads exceeding a period of 6 hours should be avoided because then VFA may accumulate to a detrimental level.

(iv) The UASB reactors are NOT ROBUST with regard to effluent variability. The effluent of the UASB reactors fluctuates in the same range of the influent COD variation, either under shock loads or under "steady state" conditions. This means that the UASB reactors are unable to attenuate fluctuations in the influent COD. The reactors show better performance in case of a hydraulic shock load, as the variation of the settled effluent is half of the variation of the imposed variation in the flow rate.

(v) A secondary treatment unit generally needs to be installed for UASB reactors operated in a regime without intentional sludge discharge, in order to cope with the sludge washout that will temporarily occur due to imposed hydraulic or organic shock loads.

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SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7

ROBUSTNESS OF THE UASB REACTORS UNDER DIFFERENT OPERATIONAL CONDITIONS: STEADY STATE AND TRANSIENT BEHAVIOUR

Although anaerobic processes have distinct advantages over aerobic processes, doubts and prejudices still exist regarding the use of this type of system in centralised sewage treatment plants. The main technical concerns are related to the robustness and stability of high rate anaerobic systems, such as Upflow Anaerobic Sludge Blanket (UASB) reactors. This PhD thesis presents results and discussions to elucidate the matters of robustness and stability of the UASB reactors for the treatment of municipal wastewater in tropical countries. The experimental investigation was carried out utilizing a set of 11 pilot-scale UASB reactors (120L) operated at different hydraulic retention times (HRT) and influent COD concentrations (COD_{Inf}). The reactors were submitted to different operational situations, i.e. under "steady state" and shock load conditions. The results obtained during this study show that the UASB reactor is very robust in terms of COD removal efficiency, as it maintains its maximum treatment performance for a wide range of operational situations when operated under "steady state". Moreover, when imposing a 6-hours organic or hydraulic shock load, the UASB reactors could maintain approximately the same COD removal efficiency as during "steady state" (based on the 24-hours average COD removal efficiencies). In addition, the pH stability of these systems is extraordinarily high (robust), even when operated under extreme operational situations, rarely occurring in municipal wastewater treatment plants. When a shock load is imposed, the UASB reactors need a very short time to recover (less than 24 hours). However, the reactors are not capable (not robust) to attenuate the fluctuations in the influent COD concentration, as the effluent fluctuates in the same range of the influent, either under "steady state" or shock load conditions. Regarding this matter, the robustness of the reactors can be improved by implementing a secondary unit for suspended solids removal.

7.1. INTRODUCTION

Although anaerobic processes have distinct advantages over aerobic processes, doubts still exist regarding the applicability of this type of system in centralised sewage treatment plants. The main technical concerns are related to the robustness and stability of high rate anaerobic wastewater treatment systems (AnWT), such as Upflow Anaerobic Sludge Blanket (UASB) reactors.

With respect to reactor performance under "steady state" conditions, there are currently a large number of papers reporting the results of the anaerobic treatment of domestic sewage. However, there was little reliable information about the operational limits of UASB reactors for the treatment of municipal wastewater. Moreover, the definition of "robustness" of an anaerobic reactor was unclear in the related literature. In the present study, robustness was defined (i) as the capacity of the system to maintain the required effluent quality during "steady state" conditions; and (ii) as the capacity to cope with more severe environmental and operational variations. In the discussion of Chapters 2, 3 and 4 (first part of the experimental research), the first definition of the robustness was used. In Chapters 5 and 6 (second part of the experimental research), the discussions about the robustness of UASB reactors are based on the second definition. In fact, the understanding of the capacity of the UASB reactors to withstand shock loads is still obscure for many users, which sometimes has led to a lack of confidence on the AnWT concept in general, and has led to a certain prejudice on the use of anaerobic reactors for pre-treatment of municipal sewage.

In brief, this PhD thesis presents experimental results and discussions which aim to elucidate the matters of performance and robustness of UASB reactors for the treatment of municipal wastewater in tropical countries. The research focuses on (i) establishing the effect of the main operational parameters (hydraulic retention time - HRT, influent concentration - COD_{Inf}, organic loading rate - OLR, and sludge retention time - SRT) on the UASB performance under "steady state" conditions, and (ii) establishing the response of the system when submitted to transient conditions.

FIRST PART OF THE EXPERIMENTAL RESEARCH: "STEADY STATE" CONDITIONS

7.2. PERFORMANCE AND STABILITY OF UASB REACTORS UNDER DIFFERENT OPERATIONAL CONDITIONS

In **Chapter 2**, experimental data were collected in order to evaluate the "steady state" performance and robustness of UASB reactors on the basis of (i) COD removal efficiency, (ii) effluent variability, and (iii) operational and pH stability. The experimental investigation was performed using 11 pilot-scale UASB reactors (120L) which were divided into three sets: Set 1, five reactors were operated with the same hydraulic retention time (HRT = 6h) and different influent COD concentrations, ranging from 92 to 816mg/L. Set 2, four reactors were operated with approximately the same influent concentration (COD_{Inf}~800mg/L), but with different HRTs, ranging from 1 to 6 hours. Set 3, the HRTs were identical to Set 2 but the COD_{Inf} was adapted to have approximately the same organic loading rate (OLR) in the four reactors (~ 3.3kgCOD/m^3.day).

The results show that at influent concentrations lower than 300mgCOD/L, the COD removal efficiency of the UASB reactors decreases with decreasing COD_{Inf}, while at COD_{Inf} values exceeding 300mg/L, the reactors attain their maximum efficiency, viz. 59% for efficiency based on total effluent COD and 77% for efficiency based on settled effluent COD. Despite our expectation that the reactor performance would be very poor when operated at low influent concentration, the UASB reactors were capable of treating sewage with an average COD_{Inf} as low as 92mgCOD/L (with suspended COD of 55mg/L), attaining efficiencies higher than 66% (based on settled effluent). The relatively high efficiency at lower influent concentration could mainly be attributed to the high removal of suspended solids (97%). However, such a low influent concentration caused high fluctuations in the performance of the reactor, i.e. frequent sludge washout events, and high variability of settled effluent COD and removal efficiency.

The results indicate that at an HRT in the range of 1 - 6 hours, the efficiencies increase with increasing HRT. Short HRTs lead to increased sludge washout (up to 130mgVS/L) as well as to lower suspended solids removal efficiencies (60.2% for HRT=1h). Moreover, under conditions of short HRT, the short contact time and short SRT cause an incomplete hydrolysis. The results also show that the COD removal efficiency based on settled effluent tends to become constant at around 77% for HRT values exceeding 4 hours. This is an indication that there is no merit to design a UASB reactor with an HRT exceeding values of 4 to 6 hours for the treatment of municipal wastewater in tropical countries, with concentrations in the range of 300 – 800 mgCOD/L.

The experiments show that for a particular HRT, the UASB reactors maintain approximately the same COD removal efficiency irrespective of the influent COD concentration (at least in the range of 300 – 800mgCOD/L). When a particular organic load from a municipality is to be treated, the COD concentration may increase when dilution with other waters (rain, infiltration) is avoided. When this happens, the flow rate decreases and the reactor can be designed with a smaller volume without deteriorating the performance.

The variability of the effluent COD concentration is highly dependent on that of the influent, while the effluent fluctuations tend to increase even more at shorter HRTs and/or decreased influent concentrations. This indicates that UASB reactors cannot attenuate the effect of daily fluctuations of the influent on the effluent.

UASB reactors treating municipal wastewater in tropical countries are extremely stable with regards to pH and buffer capacity. It is very difficult to arise an operational or environmental situation which would result in acidification. This high stability is mainly due to the characteristics of the type of wastewater used in this research, because it inherently possesses a high (potential) bicarbonate buffer capacity, and so a pH-drop can hardly occur. The observed pH-stability therefore is not really a feature of the applied AnWT system. In this investigation, slight evidences of pH instability were only noticeable under extreme operational conditions, such as an operation with an HRT shorter than 2 hours and/or influent concentration lower than 200mgCOD/L.

7.3. THE EFFECT OF OPERATIONAL CONDITIONS ON THE SLUDGE SPECIFIC METHANOGENIC ACTIVITY AND SLUDGE BIODEGRADABILITY

The specific methanogenic activity (SMA) and the biodegradability of the anaerobic sludge depend on various operational and environmental conditions imposed to the system. This part of the investigation, described in **Chapter 3**, aims to elucidate the effects of hydraulic retention time, upflow velocity and influent COD concentration on these two anaerobic sludge characteristics.

The experimental investigation was carried out using sludge obtained from eight of the 11 pilot-scale UASB reactors described in Chapter 2.

The results reveal that a higher SMA was found for sludges produced in reactors operated at shorter hydraulic retention times (higher upflow velocities). This phenomenon was attributed to at least one of the following reasons: (i) a selective retention of sludge with a high SMA at higher upflow velocities, and (ii) a high concentration of biomass growing under the high volatile fatty acids (VFA) loading rate imposed when the reactors were operated at a short HRT. In contrast, the effect of COD_{Inf} on the SMA is still not clear. The influent concentration in the range of 200-800mgCOD/L hardly affects the SMA.

The sludge biodegradability was found to be higher in reactors operated at a shorter HRT. This can be explained by the fact that reactors operated at short HRTs are inherently also submitted to high OLR, and in case of sewage, generally also to a high suspended solids (SS) loading rate. This high amount of entrapped suspended solids reduces the SRT, and therefore increases the biodegradability of the sludge. The results show that the high concentration of biodegradable material is also due to the high concentration of methanogenic biomass, which grew under the high VLRs that occur in reactors operated at shorter HRTs. Reactors operated with low COD_{Inf} produce sludges with a lower biodegradability than reactors operated with high influent concentration. This is because for a given HRT, the low total influent COD also generally implies a low SS concentration, which leads to long SRT and therefore low biodegradability of the sludge. Only the sludge produced in UASB reactors operated at HRT of 6 hours and with COD_{Inf} below 500mgCOD/L are sufficiently stable based on the requirements of EPA for landfill disposal.

In this chapter, the capacity of the UASB reactors to cope with shock loads was also evaluated on the basis of their Maximum Methanogenic Potential (MMP) and the imposed VFA loading rate loading rate (VLR). The results reveal that the "extra" VFA loading capacity of the system (MMP minus VLR) significantly decreases when it was operated at a longer HRT. This fact gives an indication of the capacity of the reactors to withstand shock loads. It also shows that it is senseless to design an UASB reactor with HRTs exceeding 6 hours, if the aim is to increase its capacity to cope with organic shock loads.

7.4. THE EFFECT OF OPERATIONAL CONDITIONS ON THE HYDRODYNAMIC CHARACTERISTICS OF THE SLUDGE BED

Chapter 4 aims to evaluate the hydrodynamic properties of the UASB sludge bed based on its settleability (compactability) and expansibility. For this purpose, the methodologies used for the assessment of the settleability of aerobic activated sludge, and of the expansibility of the sludge bed of EGSB and FBR reactors were adapted.

The experimental investigation was carried out, using sludge obtained from 7 out of the 11 pilot-scale UASB reactors described in Chapter 2.

It is clear that the operational conditions significantly affect these hydrodynamic characteristics of the anaerobic sludge bed. The biomass retention in UASB reactors is directly related to the sludge flocculation, as well as to the settleability and expansibility of the sludge bed. For both parameters, the liquid upflow velocity is the main controlling factor. Thus, the sludge retained in the reactor is intrinsically able to cope with the imposed upflow velocity, i.e. the higher the upflow velocity the higher the settleability, and the lower the expansibility. However, the role of the influent concentration in the hydrodynamic properties of the sludge is much more subtle. In this work, it was proved that reactors operated with low influent concentrations produce more flocculent, less settleable and more expansible sludge.

The experimental set-up and the procedure present in this work are very suitable for assessing the settleability (compactability) and expansibility of the anaerobic sludge. The settleability test developed in this work can be useful for designing a secondary settler, by which the treatment performance of the system can be significantly improved. Moreover, the expansibility test can be used to optimise the level of the top of the sludge bed, when the UASB reactor has to cope with significant fluctuations of the flow rate.

The results show that sludge volume index (SVI) does not represent an adequate means to compare the settleability of the sludge of different UASB reactors, since this kind of sludge is highly settleable and seems to be out of the range for the use of the SVI-method. Moreover, no relation was found between the SVI values and the settleability characteristic of anaerobic sludges.

Finally, the results in Chapter 4 show that it is worthless to design a reactor with longer HRT in order to cope with a hydraulic shock, as a more expansible sludge will develop, which is less able to withstand flow variations.

SECOND PART OF THE EXPERIMENTAL RESEARCH: SHOCK LOAD CONDITIONS

7.5. THE EFFECTS OF OPERATIONAL AND ENVIRONMENTAL VARIATIONS ON THE ANAEROBIC WASTEWATER TREATMENT SYSTEMS: A REVIEW

Based on the literature review presented in **Chapter 5**, it can be concluded that operational and environmental variations do exist, and always exert an effect on wastewater treatment systems. The extent of the impact on the system not only depends on factors related to the treatment system, but also on the type of variation imposed to the operational conditions.

In general terms, it can be said that anaerobic reactors behave in a rather similar way when exposed to some abrupt change in operational or process conditions. Organic load variations can lead to an accumulation of volatile fatty acids (VFA), a drop in pH and alkalinity values, an inhibition of methanogenic activity and possibly a decrease in the sludge retention time (SRT). Hydraulic load variations clearly affect the dynamics of the sludge bed. Depending upon whether the flow rate increases or decreases, the sludge bed will expand or shrink until a new equilibrium situation is established between the upflow and sludge settling velocities. Depending on the variation in the HRT, a higher or lower suspended solids (SS) concentration in the effluent can be found due to washout of lighter sludge particles, a change in the filtration capacity of the sludge bed under the influence of changing upflow velocities, and a disintegration of granules or flocks under the abrasive action of shear forces. Finally, depending upon the extent and duration of the imposed shock load conditions, the performance of the reactor may deteriorate and, in extreme cases, even collapse.

7.6. PERFORMANCE OF UASB REACTORS TREATING MUNICIPAL WASTEWATER UNDER HYDRAULIC AND ORGANIC SHOCK LOADS

One of the main concerns on the use of UASB reactors for the treatment of sewage seems to be the lack of knowledge about their capacity to withstand severe operational variations, i.e. organic and hydraulic shock loads. In **Chapter 6**, the robustness and stability of UASB reactors were evaluated on the basis of four indicators (i) the capacity of the reactors to retain the overload (COD removal efficiency), (ii) the extent of the effluent fluctuation following a shock load (effluent variability), (iii) pH stability during shock loads; and (iv) the period needed for the reactor to return to the performance situation prior to the shock loads (recovery time).

The experimental investigation was carried out using sludge obtained from six of the 11 pilot-scale UASB reactors described in Chapter 2.

Organic shock loads were imposed to the system by increasing the influent concentration approximately five times during a six-hour period, keeping the HRTs constant. Hydraulic shock loads were performed by increasing the flow rate three times during the same period (six hours), while the influent concentrations were kept almost constant.

Organic Shock Load

After the organic shock load started, the reactor performance temporarily deteriorated, which was mainly due to the increased settled effluent COD and the higher sludge washout. The cause of the deterioration of the settled effluent COD can be attributed to the higher effluent VFA concentration, clearly demonstrating that the reactors were overloaded. The sludge washout was mainly due to the expansion of the sludge bed at a higher gas production during the increased OLR.

In general, when organic shock load is imposed, the reactors operated with lower influent concentrations and shorter HRTs resulted in higher COD removal efficiencies (based on the 24-hours average of settled effluent). This can be attributed to the higher “reserve” capacity of these reactors to cope with organic shock loads. However, the relatively high sludge washout of reactors operated at HRTs of 4 and 2 hours caused a deterioration of the total effluent COD.

The settled effluent COD concentration (based on a 6-hour average) increased 400-800%, compared to the “steady state” values, for all reactors operated under a shock load of 5 times the influent concentration. This is an indication that the UASB reactors cannot attenuate strong fluctuations in the influent concentration.

The recovery time of an organic shock load is highly dependent on the HRT. Reactors operated at an HRT of 6 hours needed 14 to 18 hours after the cessation of the shock to return to the “steady state conditions, whilst reactors operated at a shorter HRT needed 4 to 6 hours.

There was a trend for the reactor contents to acidify in almost all cases when the five-fold organic shock loads were imposed. This was reflected in the high effluent VFA concentration and in the ratio VFA/bicarbonate alkalinity that was far beyond the risky level.

Hydraulic Shock Load

After the hydraulic shock load started, the total effluent COD immediately increased, reaching a peak within the first two or three hours. This peak was mainly caused by sludge washout as a consequence of the high upflow velocity and gas production on the dynamics (expansion) of the sludge bed. In cases when the reactors were operated with low influent concentrations, the oxygen content in the influent during the hydraulic shock may have caused a certain inhibition of the methanogenesis, as the VFA concentration increased until the shock ceased.

The reactors operated at lower influent concentration showed lower COD removal efficiency (based on a 24-hour average settled effluent) when a hydraulic shock load is imposed. In these cases, the decreased capacity to entrap the suspended solids (either the non-settleable or the excess sludge) was the main cause for the deterioration of the reactors' performance.

The settled effluent COD varied in the range of 120-240% for all reactors operated under a shock load of 3 times the flow rate. However, the total effluent COD varied up to 2300% during the transient conditions due to the heavy sludge washout. A secondary unit seems essential to mitigate such effects.

The recovery time of a hydraulic shock load was always very short. The values for settled effluent COD achieved those of the "steady state" conditions within at maximum 3 hours after the shock load ceased.

In most cases, the pH remained almost unaffected by the three-fold hydraulic shock loads. However, the effect of a long-term hydraulic shock on reactors operated with low influent concentration is unclear, since the high oxygen load imposed to the systems may have a detrimental effect.

Based on the results obtained, it can be concluded that, under tropical conditions: (i) The UASB reactors are ROBUST with regards to their ability to (partially) retain the short-term (6 hours) organic and hydraulic shock loads, because approximately the same COD removal efficiency (based on 24-hours average of the settled effluent) can be maintained as found under "steady state" conditions. (ii) The UASB reactors treating sewage are also ROBUST with regards to pH stability when exposed to three-fold hydraulic shock loads. Even when reactors were operated under extreme conditions, the pH, bicarbonate alkalinity or buffer capacity did not change significantly. (iii) The UASB reactors can withstand imposed organic shock loads up to 5 times during six hours as far as pH is concerned. However, the reactors operated with usual HRT (4 or 6 hours) and COD_{Inf} (300 – 800mg/L) resulted in a steady accumulation of VFA, and the system showed signals that acidification might take place upon continuation of the shock load. (iv) The UASB reactors have no capacity to attenuate strong fluctuation in the influent COD, and therefore in that respect could be designated as NOT ROBUST. The effluent of the UASB reactors fluctuates in the same range as the influent COD variation, either under shock loads or under "steady state" conditions. The reactor showed to be better capable to cope with a hydraulic shock load compared to an organic shock load, as the variation of the settled effluent was half of the imposed variation in the flow rate. (v) A secondary treatment unit is always necessary to retain the expelled sludge due to a hydraulic shock loads in case the UASB reactor is operated without intentional sludge discharge.

7.7. FINAL DISCUSSION, CONCLUSIONS

This main objective of this research was to evaluate the robustness or stability of the UASB reactor for the treatment of municipal wastewater under tropical conditions. This AnWT is excellent for pre-treatment of sewage. However, sewage is known to be a "problematic" type of wastewater due to its complexity and variability. The structure of the entire research, including the main conclusions, is shown in Figure 7.1.

Wastewater management companies in Brazil, particularly those in the Northeast region, are reluctant to use this kind of system for centralised wastewater treatment plants. This is mainly due to bad experiences with the first reactors implemented in NE region. The first UASB reactors were not only badly designed, but there were also problems with respect to the absence of skilled operators and a lack of budget for adequate maintenance and upgrading. The performance of these systems deteriorated due to the unplanned procedure of sludge discharge.

The performance of UASB reactors was tested under conditions of maximum retention capacity of sludge. In fact, this is similar to what was described above for the poorly operated full-scale systems in Northeast of Brazil, i.e. comprising reactors without intentional sludge discharge. The performance of the reactors was also evaluated on the basis of the settled effluent samples, and the stability of the expelled sludge as well. This operational approach simulates a system that has some type of suspended solids separation step, like a secondary settler or a pond.

This kind of operation offers interesting possibilities from the point of view of the design and operation procedures for UASB reactors:

(i) Operating an UASB reactor at maximum sludge retention capacity will improve its methanogenic potential and also the SS entrapment capacity, as the sludge bed is maintained in its maximum volume and height. However, all the excess sludge produced leaves the system with the effluent, implying that the sludge has to be retained in another treatment unit previously designed for such purpose.

(ii) The implementation of a treatment unit to retain the excess sludge improves the robustness of the overall treatment system. This is because this unit can decrease the effluent variability which occurs due to the natural events of sludge expelling, as well as the sludge washout pulses which occur when a variation in the hydraulic or organic load is imposed. In this case, the sludge has to be discharged from this post treatment.

(iii) If a secondary settler is implemented, another operational alternative arises: the sludge accumulated in the settler can be either pumped back to the reactor (in the case of a heavy sludge washout due to a shock load), or it can be conveyed to a digester (if necessary) or drying beds.

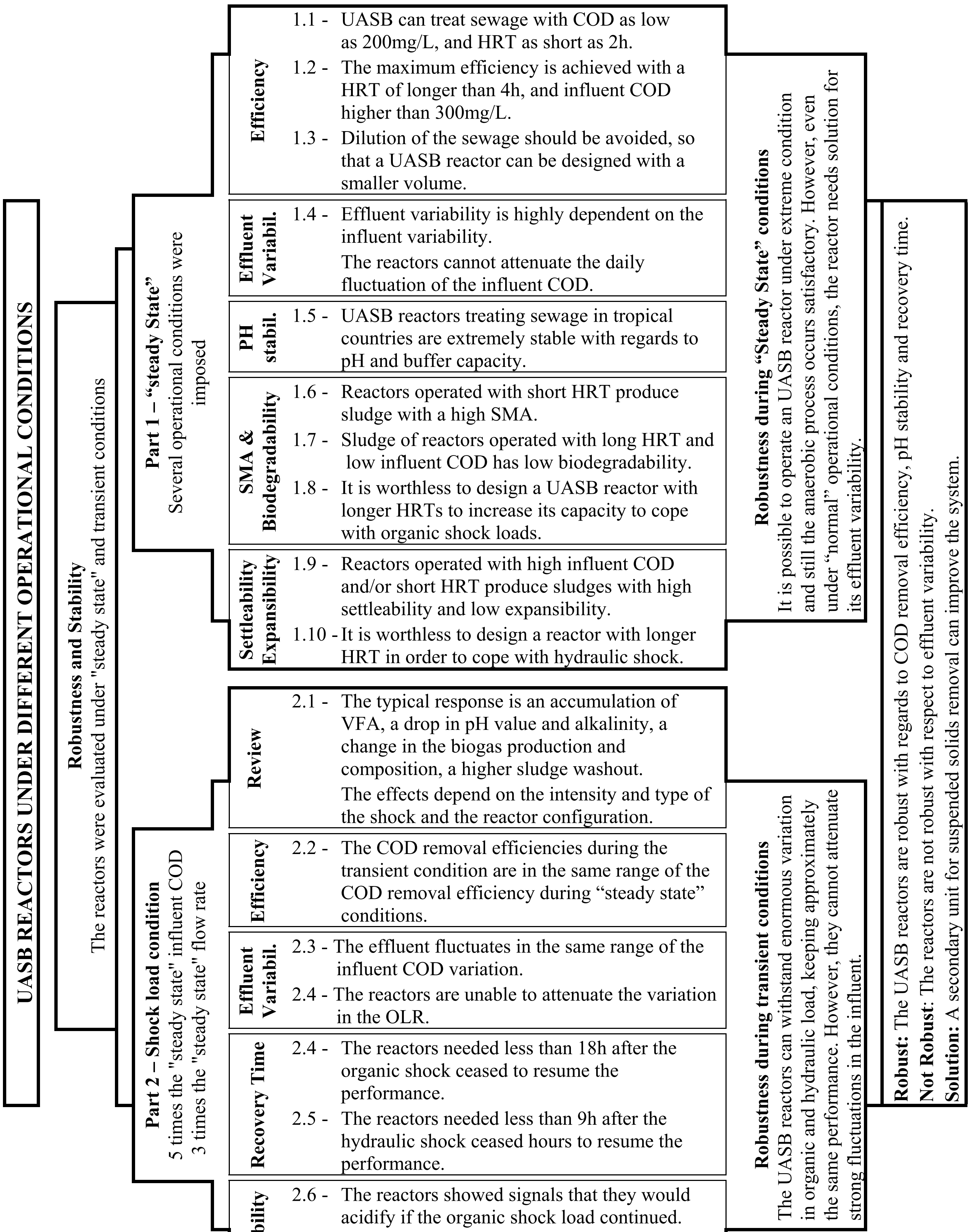


Figure 7.1 - Structure of the research, including the main conclusions.

(iv) The UASB reactor for the treatment of sewage in tropical countries (with concentrations in the range of 300 – 800mgCOD/L) may be designed with an HRT of 4 hours, as far as a secondary settler is installed. This is because reactors operated with an HRT of 6 and 4 hours resulted in approximately the same treatment efficiency (based on the settled effluent COD) and sludge stability.

(v) Another operational alternative is the use of the secondary settler to upgrade the hydraulically overloaded UASB reactors.

Finally, the robustness or stability of a wastewater treatment unit, as for example the UASB reactor, has to be evaluated not only on whether it can stand a certain operational condition, but also on specific indicators, i.e. required COD removal efficiency, recovery time from an organic or hydraulic variation, effluent variability, and pH stability. Generally, the treatment unit is part of a complex system and its performance affects the down stream units or water bodies. This means that fluctuations in the effluent of the UASB reactor will always have a detrimental effect on the post treatment or water body. The post treatment then has to be designed to cope with these fluctuations or it will not work properly; and in case of the water bodies, the local environmental agency will react according to the proper legislation.

7.8. RECOMMENDATIONS

Design and Operation

(i) Design a two-step system comprising a UASB reactor and a secondary settler: In tropical countries, the use of a two-step system comprising of a hydrolysis reactor and an UASB reactor, as proposed by Wang (1994)[1], is useless for the treatment of sewage with concentration between 200 and 800mgCOD/L, and a COD_{SS} fraction up to 70%. However, a two-step system composed of a UASB reactor and e.g. a secondary settler seems to be an interesting alternative. Most of the treatment takes place in the first unit, while the removal of settleable suspended solids occurs in the second unit. The expected total SS removal efficiency can exceed 90%. This two-step system has a substantially better overall performance than the one-step system at the same total HRT. The two-step system can also decrease the effluent variability (in terms of total COD), and increase the capacity of withstanding the shock loads. Moreover, the use of a secondary settler adds an alternative for the sludge management, as the accumulated sludge in the settler can be conveyed to further treatment (e.g. a sludge digester if still necessary), final

[1] Wang, K. (1994). Integrated Anaerobic and Aerobic Treatment of Sewage. Ph.D. Thesis. Wageningen, Wageningen Agricultural University. 144.

disposal, or it can be re-inoculated in the UASB reactor in the case of being washed out due to a shock load. The method presented in Chapter 4 for assessment of the sludge settleability can be used for the design of the secondary settler.

(ii) Design the UASB unit with a HRT in the range of 4 to 6 hours: This is because within this range the UASB reactor will probably perform with its maximum COD removal efficiency.

(iii) Design the UASB reactors based on the average flow rate: This is because the reactors cannot be improved by increasing the HRT to cope with organic or hydraulic load. A longer HRT leads to a decreased methanogenic potential, so that the reactor operated under HRT>6h has a worsened capacity to withstand an organic shock load. Moreover, a longer HRT leads to a more expansible sludge bed, which means that the sludge bed developed under such conditions has a reduced capacity to withstand a hydraulic shock load.

(iv) Operate the UASB reactor without sludge discharge: The present study proved that it is possible to operate an UASB reactor without intentional sludge discharge, i.e. the reactor is kept with its maximum sludge accumulation capacity. This operational mode can improve the filtration capacity of the sludge bed, and increase the maximum methanogenic capacity of the system.

(v) Discharge the sludge from the secondary settler: This procedure decreases the risk of over discharge and if necessary, the sludge can be re-inoculated in the reactor (case of heavy sludge washout).

(vi) Avoid dilution: So that an UASB reactor can be designed with a smaller volume without deteriorating the performance.

Research

(i) The two-step system UASB/Settler was merely simulated in the present study. This was carried out through the settled effluent after one hour of settling time. Therefore, it is recommended to conduct additional studies to evaluate a two-step pilot-scale system operated under different conditions.

(ii) The method used for calculation of the sludge settleability and expansibility needs standardisation.

(iii) The results of this research can be used for evaluation of existing anaerobic digestion models, or validation of new ones.

(iv) Finally, UASB reactors used for the treatment of sewage still need to be evaluated under successive organic and hydraulic shock loads.

8

ROBUUSTHEID VAN UASB-REACTOREN ONDER VERSCHILLENDE OPERATIONELE CONDITIES: GEDRAG IN STEADY STATE EN IN OVERGANGSSITUATIES

Hoewel anaërobe processen verschillende voordelen op aërobe processen hebben, bestaan er nog steeds twijfels en vooroordelen aangaande het gebruik van dit type systeem bij centrale rioolwaterzuiveringsinstallaties. De belangrijkste technische vragen betreffen de robuustheid en stabiliteit van hoogbelaste anaërobe systemen, zoals Upflow Anaerobic Sludge Bed (UASB) reactoren. Dit proefschrift bevat resultaten en discussies met als doel dergelijke kwesties wat betreft robuustheid en stabiliteit voor de toepassing van UASB-reactoren voor de zuivering van huishoudelijk afvalwater in tropische landen verder uit te diepen. In het experimenteel onderzoek werd gebruik gemaakt van 11 UASB-reactoren op pilotschaal (120 l) die werden bedreven bij verschillende hydraulische verblijftijden (HVT) en influent CZV-concentraties (CZV_{Inf}). De reactoren werden blootgesteld aan verschillende operationele condities, te weten "steady state" en schokbelasting. De resultaten van deze experimenten wijzen uit dat de UASB-reactor heel robuust is in termen van CZV-verwijdering, aangezien de maximale verwijderingspresentaties die behaald zijn onder "steady state" gehandhaafd blijven bij een divers aantal operationele condities. Bovendien, wanneer een 6 uur durende organische of hydraulische schokbelasting werd toegepast, behielden de UASB-reactoren ongeveer dezelfde CZV-verwijdering als tijdens "steady state" (gebaseerd op 24h-gemiddelde CZV-verwijderingsrendementen). Ook bleek de pH-stabiliteit buitengewoon hoog (robuust), zelfs onder extreme operationele toestanden, die gewoonlijk niet voorkomen in rioolwaterzuiveringsinstallaties. Wanneer een schokbelasting wordt toegepast hebben de reactoren gewoonlijk een heel korte tijd (minder dan 24 uur) nodig om te herstellen. UASB-reactoren blijken echter niet in staat (niet robuust) om schommelingen in influent CZV-concentraties af te vlakken; de schommelingen in de effluentconcentraties bleken in dezelfde orde van grootte zijn als de schommelingen in het influentconcentraties, zowel tijdens "steady state"-condities als tijdens schokbelasting. Wat dit betreft kan de robuustheid van de reactoren verbeterd worden door het toepassen van een nabehandelingsstap voor verwijdering van gesuspendeerd materiaal.

8.1. INTRODUCTIE

Hoewel anaërobe processen verschillende voordelen op aërobe processen hebben, bestaan nog er steeds twijfels en vooroordelen aangaande het gebruik van dit type systeem in centrale rioolwaterzuiveringsinstallaties. De belangrijkste technische vragen betreffen de robuustheid en de stabiliteit van hoogbelaste anaërobe waterzuiveringssystemen (AnW), zoals Upflow Anaerobic Sludge Bed (UASB) reactoren.

Wat betreft de anaërobe behandeling van huishoudelijk afvalwater is er een groot aantal publicaties over het functioneren van de reactor onder "steady state"-condities. Er is echter weinig betrouwbare informatie beschikbaar aangaande de operationele grenzen van UASB-reactoren voor rioolwaterzuivering. Daarnaast is de definitie van "robuustheid" van een anaërobe reactor in de genoemde literatuur niet duidelijk. In de onderhavige studie hebben wij robuustheid gedefinieerd (i) als de capaciteit van het systeem om de noodzakelijke effluentkwaliteit tijdens "steady state"-condities te behalen; en (ii) als de capaciteit om zwaardere milieu- en operationele variaties aan te kunnen. In de discussie van de Hoofdstukken 2, 3 en 4 (het eerst deel van het experimentele onderzoek), werd gebruik gemaakt van de eerste definitie van robuustheid. In de Hoofdstukken 5 en 6 (het tweede deel van het experimentele onderzoek) is de benadering van de robuustheid van UASB-reactoren gebaseerd op de tweede definitie. In feite is de begripsvorming over de mogelijkheden van UASB-reactoren om schokbelastingen te weerstaan nog steeds niet duidelijk voor veel gebruikers, wat soms heeft geleid tot een gebrek aan vertrouwen ten aanzien van AnW in het algemeen, en soms tot een zeker vooroordeel ten aanzien van het gebruik van anaërobe reactoren voor de voorbehandeling van huishoudelijk afvalwater.

Samenvattend bevat dit proefschrift resultaten en discussies die tot doel hebben dergelijke kwesties van robuustheid en stabiliteit voor de toepassing van UASB-reactoren voor de zuivering van rioolwater in tropische landen verder uit te diepen. Het onderzoek concentreert zich op (i) het vaststellen van het effect van de belangrijkste operationele parameters (hydraulische verblijftijd - HVT, influentconcentratie - CZV_{Inf}, organische belasting - OB en slibverblijftijd - SVT) op het functioneren van UASB's onder "steady state"-condities en (ii) de reactie van het systeem op overgangscondities.

DEEL 1 VAN HET EXPERIMENTELE ONDERZOEK: "STEADY STATE"-CONDITIES

8.2. FUNCTIONEREN EN STABILITEIT VAN UASB-REACTOREN ONDER VERSCHILLENDE OPERATIONELE CONDITIES

In **Hoofdstuk 2** werden experimentele gegevens verzameld om het functioneren en de robuustheid van UASB-reactoren onder "steady state"-condities te evalueren op basis van (i) de CZV-verwijdering, (ii) de variatie in de effluentconcentraties en (iii) de operationele en pH-stabiliteit. In het experimenteel onderzoek werd gebruik gemaakt van 11 'pilotschaal' UASB-reactoren (120 l) die waren onderverdeeld in drie groepen: Groep 1, vijf reactoren werden bedreven met dezelfde hydraulische verblijftijd (HVT = 6h) en verschillend influent CZV variërend van 92 tot 816 mg/l. Groep 2, vier reactoren werden met ongeveer dezelfde influentconcentratie (CZV_{Inf} ~ 800mg/L) bedreven, maar met verschillende HVT'en, variërend van 1 tot 6 uur. Groep 3, de HVT'en waren identiek aan groep 2, maar het CZV_{Inf} werd aangepast om in de vier reactoren ongeveer dezelfde organische belasting (~ 3.3kgCZV/m^3.dag) te verkrijgen.

Uit de resultaten bleek dat bij influentconcentraties lager dan 300mgCZV/l, de CZV-verwijdering van de UASB-reactoren afnam met afnemend CZV_{Inf}, terwijl bij CZV_{Inf}-waarden hoger dan 300mg/, de reactoren hun maximale verwijdering bereikten, namelijk 59% verwijdering op basis van totaal effluent-CZV en 77% gebaseerd op bezonken effluent-CZV. Ondanks de verwachting dat het rendement van de reactor laag zou worden bij lage influentconcentraties, bleken de UASB-reactoren in staat om afvalwater met een gemiddelde CZV_{Inf}-waarde tot 92 mg/l te zuiveren (met gesuspendeerd CZV van 55mg/l) waarbij rendementen hoger dan 66% werden bereikt (gebaseerd op bezonken effluent). Het betrekkelijk hoge rendement bij lagere influentconcentraties kon voornamelijk toegeschreven worden aan de hoge verwijdering van gesuspendeerde deeltjes (97%). Dergelijke lage influentconcentraties veroorzaakten echter grote schommelingen in de prestatie van de reactor, zoals geregelde slibuitspoeling en een hoge variatie in zowel het bezonken effluent-CZV en als het verwijderingsrendement.

Uit de resultaten blijkt dat, voor een HVT van 1 tot 6 uur, de rendementen stijgen bij toenemende HVT. Korte HVT'en leiden tot een verhoogde slibuitspoeling (tot 130mgVS/l) en ook tot lagere verwijderingsrendementen voor gesuspendeerde deeltjes (60.2% bij HVT=1h). Bovendien leidt de toepassing van een korte HVT, tot onvolledige hydrolyse door de korte contacttijd en de korte SVT. De resultaten tonen ook aan dat het CZV-verwijderingsrendement gebaseerd op bezonken effluent constant is rond waarden van 77% bij HVT'en groter dan 4 uur. Dit geeft aan dat het voor de zuivering van rioolwater met afvalwaterconcentraties van 300 – 800 mgCZV/L in tropische landen niet nodig is om een UASB-reactor te ontwerpen met een HVT groter dan 4 tot 6 uur.

De experimenten laten zien dat bij bepaalde HVT, de UASB-reactoren ongeveer hetzelfde CZV-verwijderingsrendement hebben ongeacht het influent CZV (tenminste in het bereik van 300 – 800mgCZV/l). Wanneer een bepaalde organische vracht van een plaats wordt behandeld, zal het CZV toenemen indien verdunning met ander water (regen, infiltratie) wordt vermeden. Wanneer dit gebeurt, neemt het debiet af en kan de reactor met een kleiner volume worden ontworpen zonder dat de verwijderingsprestaties verslechteren.

De variabiliteit van het effluent-CZV is sterk afhankelijk van dat van het influent. De effluentvariaties vertonen de neiging om sterker te worden bij kortere HVT en/of afgenomen influentconcentraties. Dit geeft aan dat UASB-reactoren het effect van dagelijkse schommelingen van het influent op het effluent niet kunnen afzwakken.

UASB-reactoren voor rioolwaterzuivering in tropische landen zijn extreem stabiel wat betreft pH en buffercapaciteit. Het is heel moeilijk om een operationele of milieutoestand te veroorzaken die verzuring tot gevolg heeft. Deze hoge stabiliteit is hoofdzakelijk het gevolg van de karakteristieken van dit afvalwater omdat het een hoge (potentiële) bicarbonaatbuffercapaciteit bevat, waardoor pH-dalingen amper zullen optreden. De geobserveerde pH-stabiliteit is daarom niet zozeer een eigenschap van het toegepaste AnW-systeem. In dit onderzoek werden slechts enkele geringe aanwijzingen voor een minder stabiele pH gevonden bij extreme operationele condities, zoals een experiment met een HVT korter dan 2 uur en/of influentconcentraties lager dan 200mgCZV/l.

8.3. HET EFFECT VAN DE OPERATIONELE CONDITIES OP DE SPECIFIEKE METHANOGENE ACTIVITEIT EN DE BIODEGRADEERBAARHEID VAN HET SLIB

De specifieke methanogene activiteit (SMA) en de biodegradeerbaarheid van het anaërobe slib is afhankelijk van verschillende operationele en milieucondities van het reactorsysteem. Dit deel van het onderzoek, beschreven in **Hoofdstuk 3**, had tot doel de effecten van hydraulische verblijftijd, opwaartse snelheid en influent CZV op deze twee slibkarakteristieken te onderzoeken.

Het experimentele onderzoek werd uitgevoerd met gebruikmaking van slib verkregen uit acht van de 11 pilotschaal UASB-reactoren die beschreven zijn in Hoofdstuk 2. Uit de resultaten bleek dat een hogere SMA gevonden werd voor het slib dat geproduceerd werd in de reactoren die met een kortere hydraulische verblijftijd (en hogere opwaartse snelheid) bedreven werden. Dit fenomeen werd aan tenminste één van de volgende redenen toegeschreven (i): selectief behoud van slib met een hogere SMA bij hogere opwaartse snelheden, en (ii) een hogere concentratie aan biomassa als resultaat van de hoge belasting met vluchtige vetzuren (VVZ) die optrad toen de reactoren bij een korte HVT werden bedreven. Daartegenover blijkt dat het effect van CZV_{Inf} op de SMA nog steeds niet duidelijk is. Variaties in de influentconcentratie in het bereik van 200-800mgCZV/l hebben nauwelijks effect op de SMA.

Er werd een hogere slibbiodegradeerbaarheid gevonden in reactoren die bij kortere HVT bedreven werden. De verklaring hiervoor is dat reactoren die bij korte HVT bedreven worden ook blootgesteld zijn aan een hoge OB en, in het geval van rioolafvalwater, ook aan een hoge zwevendestofbelasting. Deze grote hoeveelheid ingevangen gesuspendeerde deeltjes verlaagt de SVT waardoor de biodegradeerbaarheid van het slib toeneemt. De resultaten laten zien dat de hoge concentratie aan afbreekbaar materiaal ook het gevolg is van de hoge concentratie methanogene biomassa die onder hoge VVZ-belasting gegroeid is in de reactoren met kortere HVT. Reactoren die worden bedreven met een laag CZV_{Inf} resulteren in slib met een lagere biodegradeerbaarheid dan reactoren met een hoge influentconcentratie. Dit komt omdat bij een gegeven HVT, de lage influent CZV in het algemeen ook een lagere zwevendestofconcentratie betekent, dat weer tot een relatief lange SVT leidt en dientengevolge tot een lagere biodegradeerbaarheid van het slib. Alleen het slib dat geproduceerd werd in de UASB-reactoren die bedreven werden bij een HVT van 6 uur en met een CZV_{Inf} lager dan 500mgCZV/L bleek voldoende stabiel voor gecontroleerd storten volgens de richtlijnen van de Environmental Protection Agency.

De capaciteit van UASB-reactoren om een schokbelasting te weerstaan werd in dit hoofdstuk ook geëvalueerd met behulp van de Maximale Methanogene Potentieel (MMP) en de aangelegde VVZ-beladingscapaciteit (VB). De resultaten tonen aan dat de "extra" VVZ-beladingscapaciteit van het systeem (MMP minus VB) beduidend afneemt bij hogere HVT. Dit is een indicatie voor de capaciteit van de reactoren om schokbelastingen te weerstaan. Het toont aan dat het niet zinvol is om een UASB-reactor met een HVT langer dan 6 uur te ontwerpen als methode om daarmee voldoende capaciteit te hebben om organische schokbelastingen aan te kunnen.

8.4. HET EFFECT VAN OPERATIONELE CONDITIES OP DE HYDRODYNAMISCHE KARAKTERISTIEKEN VAN HET SLIBBED

Hoofdstuk 4 heeft tot doel om de hydrodynamische eigenschappen van het slibbed van de UASB te evalueren op basis van bezinkbaarheid ('comprimeerbaarheid') en expandeerbaarheid. Hiertoe zijn de methoden voor de beoordeling van de bezinkbaarheid van aëroob actief-slib en van de slibbedexpansie van EGSB- en FBR-reactoren gebruikt.

Het experimentele onderzoek is uitgevoerd met slib van 7 van de 11 pilotschaal UASB-reactoren die beschreven zijn in Hoofdstuk 2.

Het is duidelijk dat de operationele condities een sterke invloed hebben op de hydrodynamische karakteristieken van het anaërobe slibbed. De biomassaretentie in UASB-reactoren is rechtstreeks gerelateerd aan de mate van slibvlokking en aan de bezinkbaarheid en de expandeerbaarheid van het slibbed. Voor beide parameters is de opwaartse vloeistofsnelheid de belangrijkste kritische factor. Het slib dat in een bepaalde reactor wordt vastgehouden is intrinsiek in staat om om te gaan met de opgelegde opwaartse snelheid. Door een hogere opwaartse snelheid ontstaat een hogere bezinkbaarheid en een lagere expandeerbaarheid. Het effect van de influentconcentratie op de hydrodynamische eigenschappen van het slib is echter veel subtieler. In deze studie werd aangetoond dat reactoren die bedreven worden bij lage influentconcentraties slib produceren dat vlokkiger, minder bezinkbaar en meer expandeerbaar is.

De experimentele opstelling en de meetprocedure die beschreven zijn in deze studie zijn zeer geschikt voor beoordeling van de bezinkbaarheid (comprimeerbaarheid) en de expandeerbaarheid van het anaërobe slib. De ontwikkelde bezinkingstest kan nuttig gebruikt worden voor het ontwerpen van een nabezinker, waardoor de verwijderingsprestaties van het systeem beduidend kunnen verbeteren. Daarnaast kan de expandeerbaarheidstest gebruikt worden om het maximale niveau van het slibbed te optimaliseren, indien er aanzienlijke schommelingen in de opstroomsnelheid van de UASB-reactor verwacht worden.

De resultaten laten zien dat de slibvolume-index (SVI) geen geschikte methode is om de bezinkbaarheid van het slib van verschillende UASB-reactoren te vergelijken, omdat dit type slib zeer bezinkbaar is en buiten het bereik van de SVI-meetwaarden blijkt te liggen. Er werd bovendien geen relatie gevonden tussen de SVI-waarde en de bezinkingseigenschappen van de verschillende anaërobe slibmonsters.

Tenslotte laten de resultaten die beschreven zijn in Hoofdstuk 4 ook zien dat het, met het oog op een hydraulische schokbelasting, onnodig is om een reactor met langere HVT te ontwerpen. Hierin zal zich namelijk een meer expandeerbaar slib ontwikkelen dat minder bestand is tegen variaties in de opwaartse stroming.

DEEL 2 VAN HET EXPERIMENTELE ONDERZOEK: SCHOKBELASTING

8.5. DE RESULTATEN VAN OPERATIONELE EN MILIEUVARIATIES OP ANAËROBE AFVALWATER BEHANDELING SYSTEMEN: LITERATUURSTUDIE

Uit de literatuurstudie die beschreven is in **Hoofdstuk 5** kan geconcludeerd worden dat operationele en milieuvariaties in afvalwaterzuiveringssystemen bestaan en altijd een effect zullen hebben. De omvang van het effect hangt niet alleen af van de ontwerpfactoren met betrekking tot het zuiveringssysteem, maar ook van het type variatie dat wordt toegepast op de operationele condities.

In het algemeen kan worden opgemerkt dat anaërobe reactoren op gelijke wijze reageren wanneer ze blootgesteld worden aan abrupte veranderingen in de operationele of procescondities. Variaties in de organische belasting kunnen leiden tot een ophoping van vluchtige vetzuren (VVZ), een pH-verlaging, remming van de methanogene activiteit en mogelijk een afname in de slibverblijftijd (SVT). Variaties in de hydraulische belasting hebben duidelijk effect op de dynamische eigenschappen van het slibbed. Afhankelijk van of de opstroomsnelheid toeneemt of afneemt, zal het slibbed uitzetten of krimpen, tot een nieuwe evenwichtstoestand wordt bereikt tussen de opwaartse snelheid en de bezinksnelheid van het slib. Afhankelijk van de variatie in de HVT, zal in het effluent een hogere of lagere concentratie gesuspendeerde deeltjes (SS) gevonden worden als gevolg van de uitspoeling van lichtere slibdeeltjes, veranderingen in de filtratiecapaciteit van het slibbed onder invloed van veranderende opwaartse snelheden en de disintegratie van slibkorrels of slibvlokken door de schurende werking van wrijvingskrachten. Tenslotte kan het functioneren van de reactor, afhankelijk van de omvang en de duur van de opgelegde schokbelastingen, verslechteren of, in extreme gevallen, zelfs volledig stoppen.

8.6. HET FUNCTIONEREN VAN UASB-REACTOREN VOOR RIOOLWATER-ZUIVERING BIJ HYDRAULISCHE EN ORGANISCHE SCHOKBELASTINGEN

Eén van de belangrijkste punten van zorg bij het gebruik van UASB-reactoren voor rioolwaterzuivering is het tekort aan kennis aangaande de capaciteit om extreme operationele variaties, d.w.z. organische en hydraulische schokbelastingen, te weerstaan. In Hoofdstuk 6, is de robuustheid en stabiliteit van UASB-reactoren geëvalueerd aan de hand van vier indicatoren, (i) de capaciteit van de reactoren om de overbelasting in de reactor vast te houden (het CZV-verwijderingsrendement), (ii) de omvang van de effluentvariatie na schokbelasting (effluentvariabiliteit), (iii) de pH-stabiliteit tijdens schokbelastingen; en (iv) de periode die nodig is om de reactor terug te laten keren naar het oorspronkelijk functioneren van voor de schokbelastingen (de hersteltijd).

Het experimentele onderzoek is uitgevoerd met slib afkomstig van zes van de 11 pilotschaal UASB-reactoren die beschreven zijn in Hoofdstuk 2.

Het systeem werd blootgesteld aan organische schokbelastingen door de influentconcentratie ongeveer vijfmaal te verhogen gedurende een periode van zes uur, bij gelijkblijvende HVT. Hydraulische schokbelastingen werden toegepast door het influentdebiet met een factor drie te verhogen gedurende eenzelfde periode van zes uur, waarbij de influentconcentraties bijna constant werden gehouden.

Organische Schokbelasting

Na de start van de organische schokbelasting verslechterde de prestatie van de reactor tijdelijk, hoofdzakelijk tengevolge van het toegenomen bezonken effluent-CZV en de hogere slibuitspoeling. De reden van de toegenomen bezonken effluent-CZV kan toegeschreven worden aan de hogere effluent VVZ-concentratie, waaruit duidelijk blijkt dat de reactoren overbelast waren. De slibuitspoeling was hoofdzakelijk het gevolg van de uitdijing van het slibbed die weer veroorzaakt werd door de hogere gasproductie tijdens de toegenomen OB.

In het algemeen bleek dat de reactoren die bedreven werden bij lagere influentconcentratie en een kortere HVT, resulteerden in hogere CZV-verwijderingsrendementen (gebaseerd op 24h-gemiddelde waarden van het bezonken effluent) bij toepassing van een organische schokbelasting. Dit kan toegeschreven worden aan de grotere “reserve”-capaciteit van deze reactoren om organische schokbelastingen aan te kunnen. De relatief hoge slibuitspoeling van reactoren met een HVT van 4 en 2 uur veroorzaakte echter een verslechtering van het totaal effluent-CZV.

In de reactoren die werden blootgesteld aan een schokbelasting van 5 maal de influentconcentratie nam de bezonken effluent-CZV-concentratie (gebaseerd op 6h-gemiddelde waarden) toe met 400-800% vergeleken met de "steady state" waarden. Dit is een aanwijzing dat UASB-reactoren sterke schommelingen in de influentconcentratie niet kunnen afzwakken.

De hersteltijd van een organische schokbelasting is sterk afhankelijk van de HVT. De reactoren die bedreven werden met een HVT van 6 uur, hadden 14 tot 18 uur nodig na de beëindiging van de schok om weer naar "steady state"-condities terug te keren. De reactoren met een kortere HVT hadden 4 tot 6 uur nodig.

In bijna alle gevallen waarin de vijfvoudige organische schokbelasting werd opgelegd bleken de reactoren een neiging tot verzuren te hebben. Dit bleek uit de hoge effluent VVZ-concentratie en de VVZ/bicarbonaat-alkaliteitsverhouding, die ver voorbij het riskante niveau daalde.

<u>Hydraulische schokbelasting</u>

Na de start van de hydraulische schokbelasting ging het totale effluent-CZV direct omhoog en bereikte een hoogtepunt binnen twee tot drie uur. Dit hoogtepunt werd hoofdzakelijk veroorzaakt door slibuitspoeling tengevolge van de dynamiek van het slibbed (expansie, uitdijing) door de hogere opwaartse snelheid en de hogere gasproductie. Het is mogelijk dat, in de reactoren die bij lage influentconcentraties werden bedreven, de zuurstofconcentratie in het influent tijdens de hydraulische schok enige remming van de methanogenese veroorzaakt heeft, omdat de VVZ-concentratie toenam tot het einde van de schokbelasting.

De reactoren die bedreven werden bij lagere influentconcentraties gaven lagere CZV-verwijderingsrendementen te zien (gebaseerd op het 24h-gemiddelde van het bezonken effluent) bij de toepassing van een hydraulische schokbelasting. De hoofdreden van het verminderd functioneren van deze reactoren was de afgenomen capaciteit om gesuspendeerde deeltjes in te vangen.

Bij alle reactoren die onder een schokbelasting van 3 maal de opstroomsnelheid bedreven werden, varieerde het bezonken effluent-CZV van 120 tot 240%. Als gevolge van zware slibuitspoeling varieerde het totale effluent-CZV gedurende de overgangscondities tot 2300%. Een nabehandelingsstap lijkt noodzakelijk om een dergelijk resultaat af te zwakken.

De hersteltijd na een hydraulische schokbelasting bleek altijd heel kort. De waarde van het bezonken effluent-CZV bereikte de "steady state"-waarden maximaal 3 uur na het stoppen van de schokbelasting.

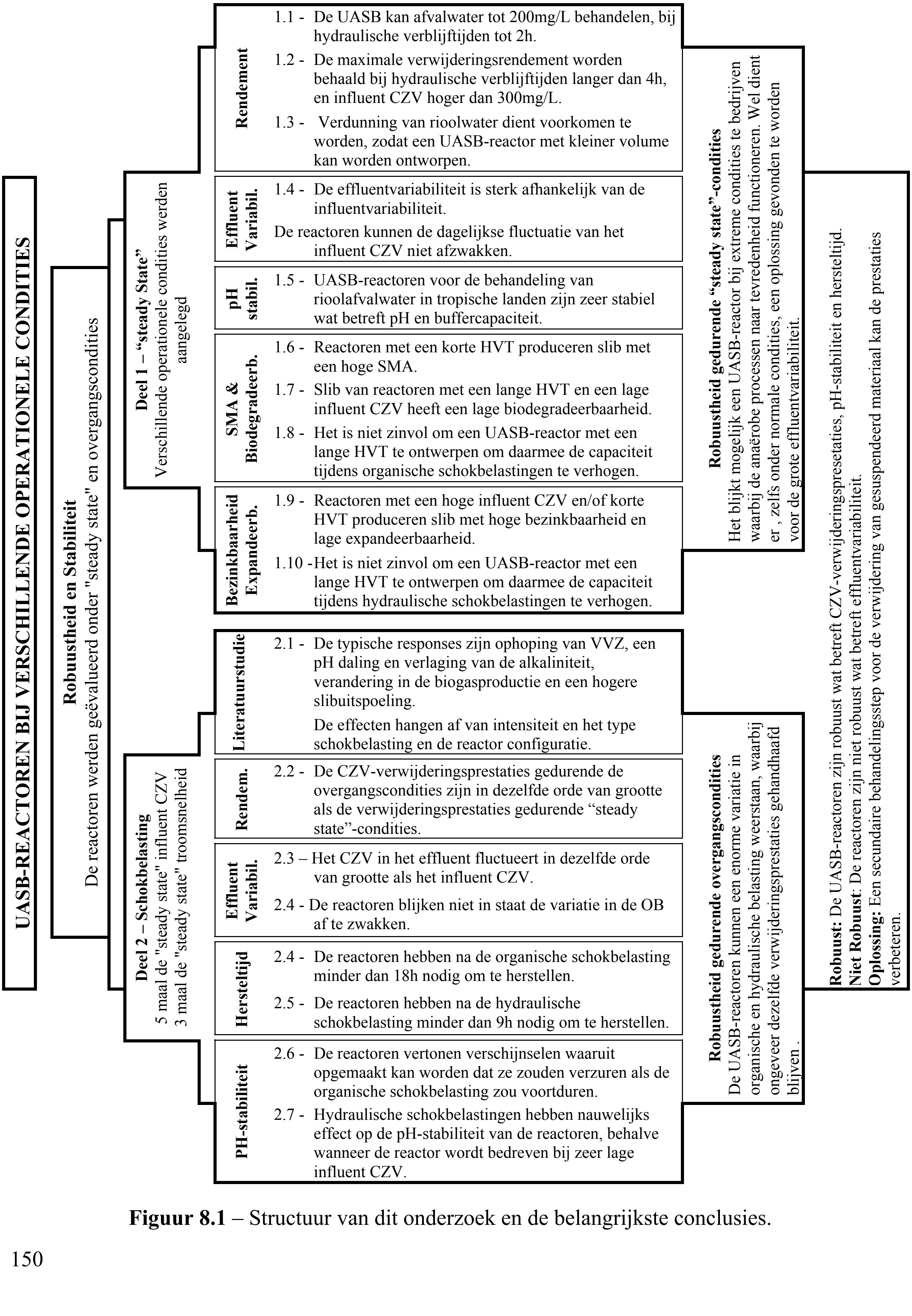
De pH bleef na de drievoudige hydraulische schokbelastingen in de meeste gevallen nagenoeg op dezelfde waarde. Het effect van een hydraulische schokbelasting op reactoren met een lage influentconcentratie op langere termijn, is echter onduidelijk; de hoge zuurstofbelasting die de systemen wordt opgelegd, zou kunnen leiden tot een nadelig resultaat.

Op basis van de verkregen resultaten kan geconcludeerd worden dat, voor rioolwaterzuivering onder tropische condities: (i) UASB-reactoren ROBUUST zijn wat betreft hun bekwaamheid om organische en hydraulische schokbelastingen gedurende korte termijn (6 uur) (gedeeltelijk) te weerstaan, aangezien ongeveer dezelfde CZV-verwijderingsrendementen (gebaseerd op het 24h-gemiddelden van het bezonken effluent) gehandhaafd kunnen worden als onder "steady state"-condities. (ii) UASB-reactoren bij blootstelling aan een drievoudige hydraulische schokbelasting ook ROBUUST zijn wat betreft pH-stabiliteit. Zelfs wanneer de reactoren onder extreme condities werden bedreven, bleken de pH, de bicarbonaatalkaliteit en buffercapaciteit niet beduidend veranderd. (iii) UASB-reactoren opgelegde organische schokbelastingen tot 5 maal de influentconcentratie gedurende zes uur kunnen weerstaan wat betreft pH. Echter, de reactoren die bedreven werden bij een HVT van 4 of 6 uur en een CZV_{Inf} van 300 – 800mg/l resulteerden in een ophoping van VVZ en het systeem toonde aanwijzingen dat verdere verzuring plaats zou kunnen vinden bij voortzetting van de schokbelasting. (iv) UASB-reactoren niet in staat zijn om sterke schommelingen in het influent CZV af te zwakken en daarom wat dat betreft kunnen worden aangemerkt als NIET ROBUUST. Het effluent van de UASB-reactoren schommelt zowel onder schokbelastingen als onder "steady state"-condities in dezelfde orde van grootte als het influent CZV. De reactor bleek wel beter in staat te zijn om een hydraulische schokbelasting aan te kunnen in vergelijking met een organische schokbelasting, aangezien de variatie in het bezonken effluent de helft was van de variatie in het influentdebiet. (v) Een secundaire behandelingsstap altijd noodzakelijk is om het uitgespoelde slib tengevolge van een hydraulische schokbelasting vast te houden indien de UASB-reactor zonder opzettelijke slibspui wordt bedreven.

8.7. SLOTDISCUSSIE, CONCLUSIES

Het hoofddoel van dit onderzoek was het evalueren van de robuustheid of stabiliteit van de UASB-reactor voor rioolwaterzuivering onder tropische condities. Deze AnW is uitstekend geschikt voor de voorbehandeling van rioolafvalwater. Het is bekend dat rioolafvalwater bekend staat als een "problematische" soort afvalwater tengevolge van de complexe en variabele samenstelling en omvang. De structuur van het volledige onderzoek, inclusief de hoofdconclusies, is in Figuur 8.1 weergegeven.

Afvalwatermanagementbedrijven in Brazilië, en in het bijzonder die in het Noordoostelijk gebied, zijn aarzelend in de toepassing van anaërobe systemen bij centrale rioolwaterzuiveringsinstallaties. Dit is hoofdzakelijk het gevolg van de slechte ervaringen met de eerste reactoren die in NO gebied zijn toegepast. De eerste UASB-reactoren waren niet alleen slecht ontworpen maar er traden ook problemen op door de afwezigheid van gekwalificeerd personeel en door tekorten aan budget voor onderhoud en verbetering. De prestatie van deze systemen verslechterde tengevolge van ongecontroleerde spui van slib via het effluent.



Figuur 8.1 – Structuur van dit onderzoek en de belangrijkste conclusies.

In deze studie is de toepassing van UASB-reactoren met maximaal behoud van slib in de reactor onderzocht. Dit is in feite een vergelijkbare toepassing als de hierboven beschreven slecht bedreven systemen in het Noordoosten van Brazilië, d.w.z. reactoren zonder opzettelijke slibspui. We hebben de prestatie van de reactoren ook geëvalueerd op basis van bezonken effluentmonsters en op basis van de stabiliteit van het uitgespoelde slib. Deze operationele benadering simuleert een systeem dat een vorm van nageschakelde deeltjesverwijdering heeft, zoals een nabezinker of een vijver.

Het op deze manier bedrijven van het systeem biedt interessante mogelijkheden voor het ontwerp en beheer van UASB-reactoren:

(i) Het bedrijven van een UASB-reactor op basis van maximaal behoud van slib zal het methanogene potentieel en ook de zwevendestofinvangcapaciteit verbeteren, omdat het slibbed op maximaal volume en op maximale hoogte kan worden gehandhaafd. Dit betekent wel dat het overtollig slib via het effluent het systeem zal verlaten en impliceert dat dit slib in een voor dit doel ontworpen nabehandelingsstap vastgehouden zal moeten worden.

(ii) De toepassing van een nabehandelingsstap om het overtollig slib vast te houden verbetert de robuustheid van het totale behandelingssysteem. Deze behandelingsstap kan namelijk de effluentvariabiliteit doen afnemen die het gevolg is van natuurlijke slibuitspoeling of van slibuitspoeling die het gevolg is van een variatie in de hydraulische of organische belasting. In een dergelijke configuratie zal het slib uit deze nabehandelingsstap gespuid moeten worden.

(iii) Bij toepassing van een nabezinker, komt nog een operationeel alternatief in beeld: het slib dat in de bezinker verzameld wordt kan teruggepompt worden naar de UASB-reactor (in het geval van een zware slibuitspoeling tengevolge van een schokbelasting), of het kan (indien nodig) overgebracht worden naar een slibvergister of naar slibdroogbedden.

(iv) De UASB-reactor voor rioolwaterzuivering in tropische landen (met concentraties in het bereik van 300 – 800mgCZV/l) kan ontworpen worden met een HVT van 4 uur, wanneer een nabezinker wordt geïnstalleerd. Dit blijkt uit het feit dat reactoren met een HVT van 6 en van 4 uur resulteerden in ongeveer dezelfde verwijderingsprestaties en slibstabiliteit (gebaseerd op het bezonken effluent-CZV).

(v) Een ander alternatief is het gebruik van een nabezinker om huidige, hydraulisch overbelaste UASB-reactoren uit te breiden.

Ten slotte moet de robuustheid of stabiliteit van een afvalwaterbehandelingstap zoals bijvoorbeeld de UASB-reactor, niet alleen geëvalueerd aan de hand van de vraag of hij specifieke operationele condities aankan, maar ook op basis van specifieke indicatoren, zoals bijvoorbeeld het noodzakelijke CZV-verwijderingsrendement, de hersteltijd na een organische of hydraulische schokbelasting, de effluentvariabiliteit en de pH-stabiliteit. In het algemeen zal een dergelijke behandelingsstap deel uitmaken van een groter systeem en zal de verwijdering effect hebben op nageschakelde behandelingsstappen of op het ontvangend oppervlaktewater. Dit betekent dat schommelingen in het effluent van de UASB-reactor altijd een nadelig resultaat op nageschakelde behandelingsstappen of op het ontvangend oppervlaktewater zullen hebben. De verdere nabehandeling zal in dat geval ontworpen moeten worden om deze schommelingen op te kunnen vangen, anders zal deze niet goed functioneren.

8.8. AANBEVELINGEN

Ontwerp en Beheer

(i) Ontwerp een tweetrapssysteem bestaande uit een UASB-reactor en een nabezinker: In tropische landen is het gebruik van een tweetrapssysteem bestaande uit een hydrolyse reactor en een UASB-reactor, zoals voorgesteld door Wang (1994)[1], niet zinvol voor de behandeling van afvalwater met concentratie tussen 200 en 800mgCZV/l en een CZV_{SS} fractie tot 70%. Echter, een tweetrapssysteem bestaande uit een UASB-reactor in combinatie met een nabezinker lijkt een interessant alternatief. Het grootste deel van de zuivering gebeurt dan in de eerste behandelingsstap, terwijl in de tweede behandelingsstap de verwijdering van bezinkbare deeltjes plaats vindt. Het totale SS-verwijderingsrendement kan de 90% overschrijden. Dit tweetrapssysteem heeft een aanzienlijk betere totale prestatie dan een ééntrapssysteem, bij dezelfde totale HVT. Door toepassing van een dergelijk tweetrapssysteem kan ook de effluentvariabiliteit (wat betreft totaal CZV) afnemen en kan de systeemcapaciteit om schokbelastingen op te vangen verhoogd worden. Het gebruik van een nabezinker maakt bovendien een alternatief slibbeheer mogelijk, waarbij het in de bezinker verzamelde slib ofwel overgebracht kan worden naar een slibbehandelingsstap (bijvoorbeeld naar een slibvergister mocht dat nog nodig zijn) of direct naar een eindafzet, ofwel, in het geval van uitspoeling ten gevolge van een schokbelasting,teruggebracht kan het worden naar de UASB-reactor. De methode die is voorgesteld in Hoofdstuk 4 voor de beoordeling van de bezinkbaarheid van het slib kan gebruikt worden voor het ontwerp van de nabezinker.

(ii) Ontwerp de UASB-reactor met een HVT van 4 tot 6 uur: Binnen deze HVT'en zal de UASB-reactor vermoedelijk met maximaal CZV-verwijderingsrendement functioneren.

(iii) Ontwerp de UASB-reactor gebaseerd op de gemiddelde opstroomsnelheid: De capaciteit van de reactoren om organische of hydraulische schokbelastingen op te vangen kan niet worden verbeterd door toepassing van een langere HVT. Een langere HVT leidt tot een lagere methanogene capaciteit, waardoor een reactor die bedreven wordt bij een HVT > 6h minder capaciteit heeft om een organische schokbelasting op te vangen. Bovendien leidt de toepassing

[1] Wang, K. (1994). Integrated Anaerobic and Aerobic Treatment of Sewage. Ph.D. Thesis. Wageningen, Wageningen Agricultural University. 144.

van een langere HVT tot een meer expandeerbaar slibbed, wat betekent dat het slibbed dat zich onder dergelijke condities ontwikkeld een verminderde capaciteit heeft om een hydraulische schokbelasting te weerstaan.

(iv) Bedrijf de UASB-reactor zonder slibspui: De huidige studie wijst uit dat het mogelijk is een UASB-reactor zonder opzettelijke slibspui te bedrijven. Dit wil zeggen dat de reactor wordt bedreven bij zijn maximale capaciteit om slib vast te houden. Deze operationele modus kan de filtratiecapaciteit van het slibbed verbeteren en verhoogt de maximale methanogene capaciteit van het systeem.

(v) Spui het slib uit de nabezinker: Deze procedure verlaagt het risico van 'overspui'. Bovendien kan het slib (in het geval van zware slibuitspoeling) worden teruggevoerd naar de UASB-reactor.

(vi) Vermijd verdunning: Hierdoor kan een UASB-reactor met een kleiner volume worden ontworpen zonder dat de prestaties verslechteren.

Onderzoek

(i) Het tweetrapssysteem UASB/bezinker is in deze studie alleen gesimuleerd. Dit is gebeurd door het effluent gedurende 1 uur te laten bezinken. Aangeraden wordt in vervolgstudies een tweetrapssysteem te onderzoeken bij verschillende procescondities.

(ii) De methoden die gebruikt zijn voor berekening van de bezinkbaarheid en expandeerbaarheid van het slib dienen gestandaardiseerd te worden.

(iii) De resultaten van dit onderzoek kunnen gebruikt worden voor de evaluatie van bestaande anaërobe vergistingsmodellen of voor de validatie van nieuwe modellen.

(iv) Tenslotte zullen UASB-reactoren voor rioolwaterzuivering nog getest moeten worden op een opeenvolgende reeks organische en hydraulische schokbelastingen.

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Renato Carrhá Leitão
Wageningen, the Netherlands, June 2004

Photo 1 – Prof. Gatze Lettinga

Photo 2 – Prof. Adrianus van Haandel

Photo 3 – Dr. ir Grietje Zeeman

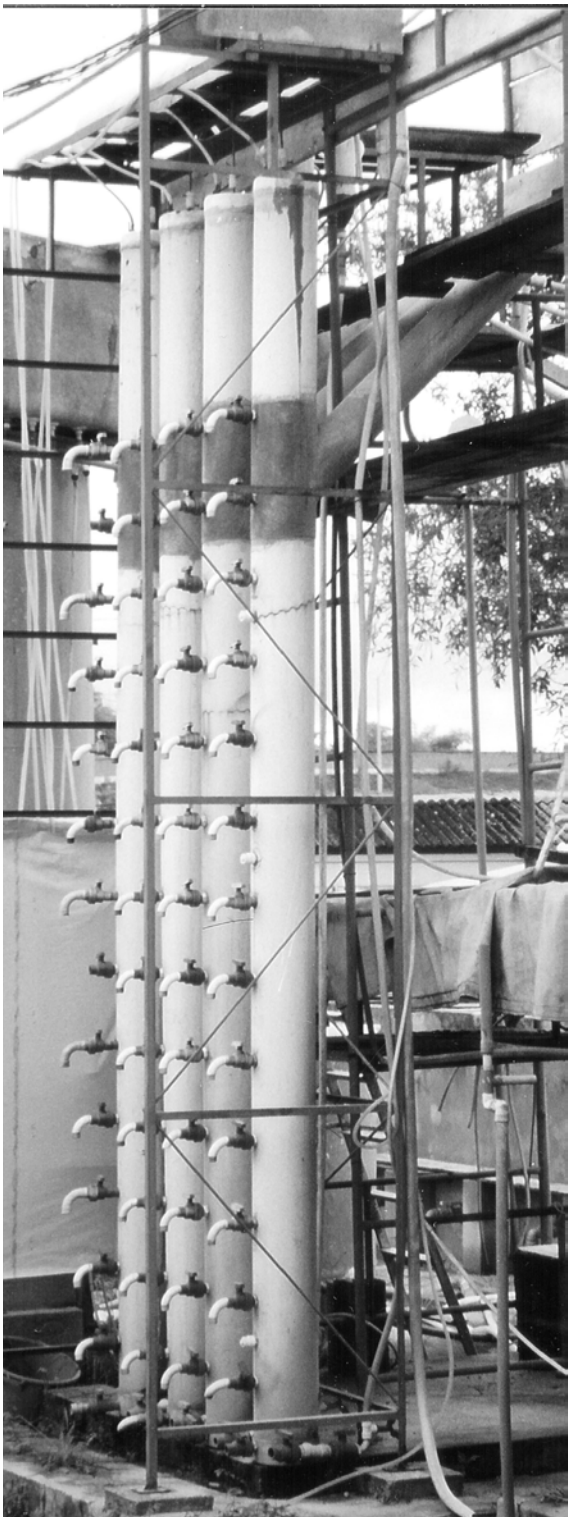

Photo 4 – The pilot-scale UASB reactors used in this research

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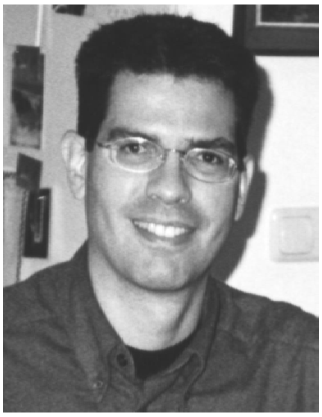

The author of this thesis, Renato Carrhá Leitão, was born on 08 December 1964 in Fortaleza, Ceará, Brazil. In 1988 he obtained his degree in Civil Engineering at the Federal University of Ceará. In 1991 he received his MSc diploma in Hydraulics and Sanitation at the São Carlos School of Engineering, University of São Paulo. From 1991 to 2000 he worked at the Water Resources office of Ceará State as design analyst; at the Meteorological and Water Resource Foundation of Ceará State as environmental engineer, at the private firm Gaia Environmental Consulting S/A as associate, and finally at the private firm Engesoft Engineering and Consulting S/A as project/design manager. In September 2000 he started his PhD at the Sub-Department of Environmental Technology at the Wageningen University, the Netherlands, with the experimental part at the Federal University of Campina Grande, Brazil. After June 2004, he intent to continue with the research work, and to transfer the knowledge he acquired during his studies in order to improve the sanitation in Brazil.

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Cover: The Y-shape of the pilot-scale UASB reactor used in this research. The graph is based on an actual organic shock load imposed to one of the reactors.