Influence of phase separator design on the performance of UASB reactors treating municipal wastewater

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ABSTRACT

The objective of anaerobic sewage treatment is to maximize the fraction of influent organic material that is transformed into methane, thus minimizing the COD fractions that are discharged with the effluent or in the excess sludge production. Experimental data in this paper show that in the case of application of a UASB reactor for sewage treatment, the phase separator design has an important influence on digestion efficiency. An efficient phase separator leads to retention of a larger sludge mass, which means that the mean solids retention time is increased. The data show that the mean solids retention time or sludge age is the fundamental operational parameter that determines the efficiency of the anaerobic treatment. A simple way to improve the phase separator performance is to apply parallel plates in the settling section of the UASB reactor, above the conventional phase separator design of triangular prisms with an open base.

Keywords: anaerobic sewage treatment, UASB reactor, phase separator design, performance optimization, sludge age.

INTRODUCTION

The two main conditions for any well-performing biological wastewater treatment system are (i) to ensure good contact between the incoming substrate and the sludge mass in the system, and (ii) to maintain a large sludge mass in the system. In the UASB reactor the influent is distributed uniformly over the bottom of the reactor and then, following an upflow pathway, rises through a thick layer of anaerobic sludge, whereafter it is withdrawn at the top of the reactor. Thus, contact between the influent organic material and the sludge mass in the reactor is automatically guaranteed. In order to maintain a large sludge mass, the UASB reactor has a built-in phase separator, where the dispersed solids are retained by settling, so that an effluent virtually free from settleable solids can be discharged. The retained sludge particles will end up sliding back from the settler compartment into the digester compartment and accumulate there, thus contributing to the maintenance of a large sludge mass in the reactor and satisfying the second condition for good performance.

Due to synthesis of biomass and flocculation of particulate influent material, there is continuous growth of the sludge mass in the reactor. However, the reactor has a certain maximum sludge hold-up and once the reactor is 'full', any new sludge production will lead to the loss of an equal sludge mass from the system. In that case, an increasing amount of sludge particles will be present in the effluent. From then onwards, the rate of (unintentional) sludge wastage will become equal to the rate of sludge production and can therefore be determined experimentally as such.

An alternative operational procedure is to periodically discharge part of the sludge mass (excess sludge), which should lead to a significant (though never complete) decrease in the sludge concentration in the effluent. In either case, it is possible to calculate the sludge age or the mean solids retention time. This is the ratio between the sludge mass present in the reactor and the rate of intentional + unintentional sludge wastage. It is important to emphasise here that, as a result of the solids retention mechanism, the solids retention time or sludge age (R_s) will always exceed the liquid retention time (R_h). The difference becomes more pronounced as the phase separator becomes more efficient. In a UASB reactor treating sewage in tropical regions usually the R_h is of the order of 4 to 8 h and R_s is in the range of 30 to 100 days (van Haandel and Lettinga, 1994), so that R_s/R_h » 100 to 600.

The performance of the UASB reactor as a unit for sewage treatment, under appropriate conditions, is quite remarkable. In regions with a hot climate (sewage temperature above 18°C), a very high removal efficiency of the organic material (65 to 80% of the influent COD) can be obtained in conventional UASB reactors with a short retention time (5 to 8 h) (Van Haandel and Lettinga, 1994; Chernicharo, 2015). This can be attributed mainly to the fact that through the application of a phase separator the sludge age becomes, at least in principle, independent of the liquid retention time. By maintaining a long sludge age, the large sludge mass that develops in the reactor enhances efficient removal of biodegradable organic material.

The deterioration of UASB reactor performance at decreasing liquid retention times must be attributed to: (i) the increasing inability of the phase separator to retain the sludge and (ii) the short time left for the retained sludge to convert the biodegradable and soluble COD. The increase of the COD fraction in the effluent is partly due to the presence of biodegradable influent material, which increases with shorter R_h. Also, sludge production increases when the R_h decreases, because part of the influent particulate and biodegradable matter is discharged before hydrolysis can take place. Hence, faecal matter mixed with bacterial sludge will be present in the excess sludge. More efficient sludge retention could lead to a decrease of escaping particulate organic material, thus reducing the COD fraction discharged together with the effluent. Moreover, the efficient

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sludge retention would cause an increase of the sludge age in the reactor, which by itself would increase not only the efficiency of hydrolysis and subsequent digestion, but also the bacterial sludge mass. Therefore, if the phase separator design is improved, a decrease in liquid retention time can be applied without reducing performance.

One option to achieve this is by applying parallel plates in the zone above the conventional phase separator, thus creating a high-rate settler, a system often used in water treatment plants. A UASB reactor equipped with such a high-rate settler will have a better performance than a reactor equipped with only a conventional phase separator, operating under comparable conditions. Equivalently, the reactor with a more efficient separator can accommodate higher loads and yet have a similar performance to the conventional reactor. Hence, the R_h may be reduced when the phase separator performance is improved.

This paper discusses results of an experimental investigation about the influence of the phase separator design on UASB reactor performance. For this purpose, the COD removal efficiency and sludge production were observed as functions of the liquid retention time in two reactors with identical dimensions and receiving the same wastewater load, but equipped with different phase separator designs. The first reactor had a conventional UASB separator (triangular prisms with an open base, (Fig. 1a) and the second had an improved design (Fig. 1b) by having parallel plates above the conventional design. The conventional phase separator is composed of prismatic elements placed in the UASB reactor, dividing it in a lower digestion zone and an upper settling section (Fig. 1a). Gas-liquid, gas-solid and solid-liquid separation occurs below the prismatic units at the interface of the liquid phase in the gas chamber. Additional solid-liquid separation occurs in the settling zone above the separator elements: particles with sufficiently high settling rates will overcome the drag force of the upward liquid flow and eventually will settle on a separator element and from there end up sliding back into the digestion zone, after a layer with enough flocculent mass has accumulated.

A floc cannot be retained if its settling velocity is lower than the upflow velocity of the liquid phase in the UASB reactor. Hence, there is a critical velocity for the retention of flocs such that:

$$s_c < v_l \qquad (1)$$

where:

s_c = critical settling velocity permitting floc retention
v_l = upflow velocity of the liquid phase (= flow/area)

If no flocculation takes place in the settling zone, only particles with a settling velocity greater than s_c will be retained and flocs with a settling velocity smaller than s_c, will be dragged out of the reactor and discharged together with the effluent.

In the alternative design depicted in Fig. 1b, the phase separator is composed of two parts. The first part is like the conventional separator and effects the separation of the biogas and part of the sludge from the liquid. The additional second part consists of parallel plates, which are placed to settle and thus retain flocs escaping from the conventional separator. Now the retention efficiency of the solids is given by the critical settling velocity in the zone with the parallel plates, which is significantly lower than the minimum settling velocity for retention in the conventional separator.

Figure 2 shows the path of a sludge particle moving between two plates: the particle enters the plate zone, next to the first plate and, as the liquid flows through the space between the plates, the particle settles and touches the second plate before the effluent leaves the plate zone. Such a particle would be retained and deposited on the plates. Eventually it would be returned to the digestion zone. From Fig. 2, while the liquid moves over a distance $l + e/\cos\alpha$, the particles to be captured settle over a distance $e{\cdot}\tan\alpha$. If the thickness of the plates is negligible, the liquid velocity between plates may be expressed as:

$$v'_1 = v_1/\sin\alpha \qquad (2)$$

Hence the ratio between the critical settling velocity to retain a particle on the plates and the liquid velocity is:(0.0)

$$s'_c/v'_1 = \text{e-tan}\ \alpha/(I + e/\cos\alpha) \qquad (3)$$

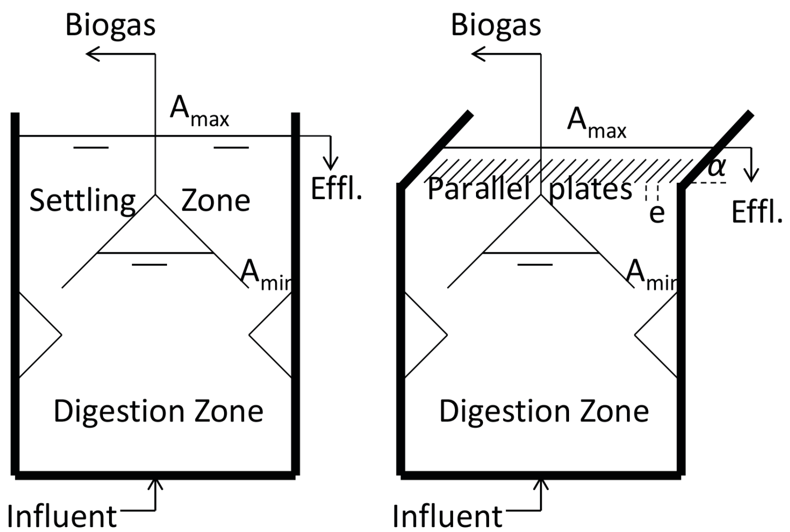

Figure 1

Different designs of phase separators for UASB reactors: (a) conventional, (b) with additional parallel plates

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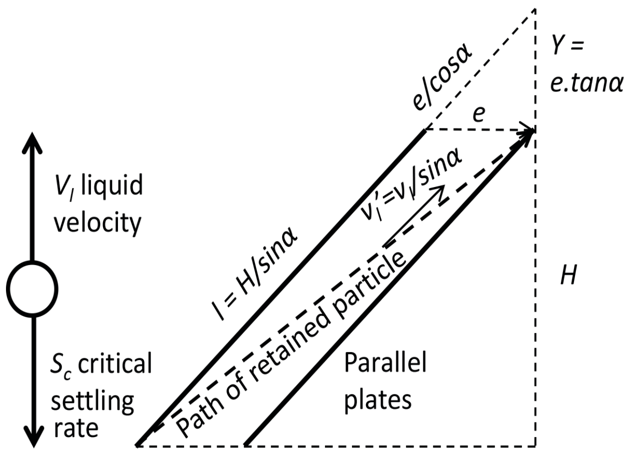

Figure 2

Representation of the settling mechanism for a conventional separator (left) and for a unit with parallel plates (right)

where:
v'_l = liquid velocity in the plates zone
s'_c = critical settling velocity in the plates zones
α = angle of the parallel plates
l = length of the plates
e = space between plates

Now the critical settling velocity for retention of a floc by the plates as given by:

$$s'_c = v'_l e \cdot \tan\alpha/(l + e/\cos\alpha) = (v_l/\sin\alpha)e \cdot \tan\alpha/(l + e/\cos\alpha)$$

and:

$$s'_c/s_c = [(v_l/\sin\alpha)e \cdot \tan\alpha/(l + e/\cos\alpha)]/s_c = 1/[l/e)\cos\alpha + 1) \quad (4)$$

Equation 4 shows that the ratio between the critical settling velocities in a separator with parallel plates and in a conventional separator, s'_c/s_c, depends on three factors: (i) the distance between plates, e, (ii) the angle of the plates α, and (iii) the height of the plate zone $H = l/\sin\alpha$. All three factors above are limited by practical considerations: (i) the distance between the plates cannot be very small to avoid problems with the removal of the sludge settled on the plates (blockages), (ii) the angle of the plates must have a minimum value to ensure the settled sludge flocs will readily slide back into the digestion zone (in practice 45 to 60°, (Valencia, 2000), and (iii) for economic reasons the depth of the zone with parallel plates cannot be very large.

Due to the lower critical settling rate in the reactor with parallel plates, it is possible to increase the hydraulic load and yet have the same efficiency of floc retention, as in the case of the reactor with only a conventional separator. It is important to note that it is **not** possible to increase the sewage flow proportional to the ratio of the respective critical settling rates, because then the organic load (and consequently the sludge production) would also increase. It is tacitly assumed that, upon retention on the plates, the individual sludge particles will agglomerate in larger particles that can be more easily retained in the reactor upon their return to the digestion zone.

An additional reason for the superior performance of the separator with parallel plates is that a portion of the flocs with a settling velocity smaller than s'_c will still be retained, depending on their position between plates, when they enter the plate zone. By contrast, in the case of the conventional separator, all flocs with a settling velocity smaller than the rising velocity of the liquid will rinse out with the effluent if no flocculation occurs.

EXPERIMENTAL INVESTIGATION

The experimental investigation was carried out using two pilot scale UASB reactors of the same size (1.2 m^3), with the objective of evaluating the effect of phase separator design on performance of the UASB reactor. The first reactor (A) had a conventional phase separator and the second (B) was equipped with additional parallel plates with. The design of Reactor B is outlined in Fig. 3. The UASB reactors were fed with a constant flow of raw municipal sewage from the main outlet of the sewer system of Campina Grande, Brazil.

The digestion zone of the reactors was formed by two connected concrete rings of 1 m height and 0.80 m diameter. The conventional phase separator, made of plexy glass, was placed in the square brickwork section that formed the settling zone, above the concrete elements. In Reactor B, parallel plates (also made of plexy glass) were placed on top of the conventional phase separator. The plates had a width of 0.5 m (depth of 0.35 m) and were placed at an angle of 45° with a spacing of 0.07 m.

The reactors were operated under identical operational conditions. The liquid retention times were varied from 12 to 1.5 hours. After imposing each particular retention time, the reactors were operated for a period of not less than 2 months before collecting the experimental data, so that a representative sludge was established. The assessed parameters were related to: (i) operational stability, (ii) organic material removal efficiency, and (iii) sludge production and composition. With respect to operational stability, the effluent pH, total alkalinity (TAlk) and volatile fatty acids (VFA) concentration were determined. For the sewage characteristics in Campina Grande (TAlk ≈ 350 mg$CaCO_3$/L, COD < 600 mg/L and T >25°C), the buffer index of the sewage was always sufficient to maintain the pH in the neutral range of 6.8 to 7.1. On the other hand, methanogenesis was always efficient: the VFA concentration in the effluent never exceeded 1 mmol/L (60 mg/L HAc) and was usually less than 0.5 mmol/L. This was true for both reactors and for the entire range of investigated retention times. Consequently, the operational stability was excellent throughout the investigation and there was no risk of souring.

Both reactors were operated without intentional discharge of excess sludge, so that the maximum sludge mass was built up, whereafter sludge rinsed out at the same rate it was produced in the reactor. The reactors were operated at constant flow rates and the experimental data were collected only after the maximum sludge hold-up had been established for each of the investigated liquid retention times.

Regarding the settleable fraction of the total suspended solids (TSS), it was considered that any particles settling in an Imhoff cone during 30 min were sludge particles and that the COD of the supernatant liquid was the true effluent COD. For this reason, both the raw and settled effluent COD were determined; the difference between the two effluent CODs was used to estimate the COD of the sludge concentration in the effluent and hence the sludge production in the reactor. Knowing that the COD of a unit mass of volatile sludge is, approximately,

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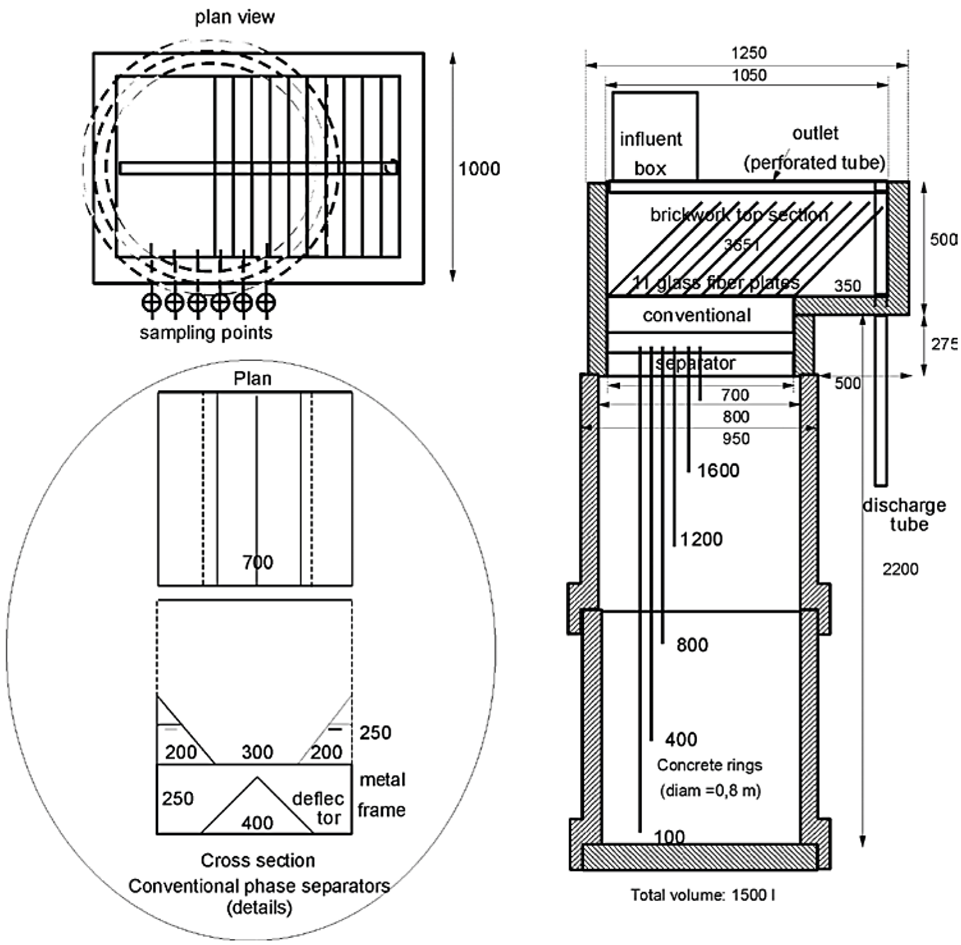

Figure 3
Representation of UASB Reactor B, used in the investigation (values in mm)

f_{cv} = 1.5 gCOD/gVSS (Marais and Ekama, 1976), the effluent volatile sludge concentration was calculated as:

$$X_{ve} = (S_{re} - S_{se})/f_{cv} \quad (5)$$

where:
X_{ve} = concentration of volatile sludge in the effluent
S_{re} = raw effluent COD concentration
S_{se} = settled effluent COD concentration

Now the sludge age is calculated as the ratio between the sludge mass in the reactor (estimated from concentration profiles at different depths) and the daily mass of discharged (= produced) sludge.

RESULTS AND DISCUSSION

Table 1 shows the influent COD concentrations as well as the raw (S_{re}) and settled (S_{se}) COD effluent values and volatile fatty acids (VFA) effluent concentrations for Reactors A and B and for the different retention times (R_h) that were investigated. In Table 2 the sludge mass and composition, in terms of gTSS/L, and its volatile fraction are also presented. The sludge mass (total and organic) was calculated from linearized concentration profiles, using the sludge concentrations at the sample points (Fig. 3). The volatile sludge production was estimated from the difference between the raw and settled effluent COD concentrations (Eq. 1). The sludge age (R_s) was calculated as the ratio between the volatile sludge mass in the reactor and the daily production found in the effluent during steady-state operational conditions.

The experimental data in Tables 1 and 2 can be used to calculate the fractions that are discharged in the effluent or as excess sludge. The digested fraction is found by the difference:

$$mS_e = S_{se}/S_{ti} \quad (6)$$

$$mS_x = (S_{re} - S_{se})/S_{ti} \quad (7)$$

$$mS_d = 1 - mS_e - mS_x \quad (8)$$

where:
mS_e = COD fraction in the effluent
mS_x = COD fraction converted into excess sludge
mS_d = digested COD fraction
S_{ti} = influent COD concentration

In Fig. 4a the values of mS_e, mS_x and mS_d, calculated from the data in Tables 1 and 2 using Eqs 2 to 4, are shown for both Reactors A and B, as functions of the applied R_h. The effluent fraction is plotted downwards from the top of the diagram. The digested fraction was not actually measured but calculated by Eq. (4) as unity minus the effluent fraction (at the top) and fraction in the excess sludge (bottom). Based on these experimental

TABLE 1
COD concentrations of influent (S_{ti}), raw (S_{re}) and settled effluent (S_{se}) and volatile fatty acids (VFA) for different retention times (R_h), in the conventional UASB reactor (A) and in the unit with an improved phase separator (B)

R_h (h)	S_{ti} (mg/L)	Reactor A			Reactor B		
		S_{re} (mg/L)	S_{se} (mg/L)	VFA (mgHAc/L)	S_{re} (mg/L)	S_{se} (mg/L)	VFA (mgHAc/L)
12	587	157	88	18	155	86	26
10	492	143	78	22	139	84	20
8	554	189	108	18	163	80	23
6	480	186	102	24	172	92	28
4	526	252	133	38	166	85	45
3	619	360	195	73	236	134	87
2	561	454	236	97	304	167	78
1	613	–	–	–	386	215	69

TABLE 2
Mean sludge concentration (TSS), volatile fraction (VF) and sludge age (R_s), as functions of liquid retention time (R_h) for reactors A and B

Sludge concentration, composition and sludge age						
	Reactor A			Reactor B		
R_h (h)	TSS (g/L)	VF –	R_s (d)	TSS (g/L)	VF –	R_s (d)
12	20.6	0.54	122	36	0.56	205
10	18.0	0.57	98	29	0.58	155
8	16.1	0.58	58	27	0.57	120
6	16.0	0.61	44	19	0.57	64
4	17.5	0.65	21	28	0.61	47
3	16.9	0.67	13	25	0.61	28
2	14.6	0.68	6	23	0.63	17
1	–	–	–	28	0.68	11

data, empirical curves were drawn for the organic material fractions as a function of R_h for the two reactors. Clearly, both fractions mS_e and mS_x increase as the R_h. decreases. This is contrary to the objective of anaerobic treatment systems, which targets minimum values for these fractions. The curves also indicate a very strong influence of the phase separator on the performance of the UASB reactor in terms of treatment efficiency. For the same digested COD fraction, the required retention time in the reactor with the improved separator (B) is about half the value required in the reactor with the conventional separator (A). Hence, the parallel plates in Reactor B led to a doubling of its volumetric treatment capacity and must be considered as a very useful means to boost the performance of UASB reactors for sewage treatment.

The data in Tables 1 and 2 can also be used to plot the three COD fractions as functions of the sludge age, as is shown in Fig. 4b (log scale for R_s). If the sludge age is used as the independent variable, the COD fractions mS_e and mS_x in Reactors A and B, in good approximation, can be described with a single curve. This means that, for any particular sludge age, the fractions of the influent COD ending up in the effluent or converted into sludge (and hence also the digested fraction) are always the same, independent of the phase separator design or the liquid retention time or even the type of anaerobic reactor that is applied. It is concluded that the sludge age and not the liquid retention time is the relevant parameter with which to describe the performance of the UASB reactor for sewage treatment. Figures 4a and 4b also reveal that, for the two reactors, there are minimum R_h and R_s values below which no methanogenesis will occur, and consequently all the organic material will leave the reactor, either in the effluent or as flocculated material in the excess sludge. The minimum R_h depends on the phase separator efficiency. The minimum R_s value depends on the maximum growth rate of the methanogens, which in turn depends on the temperature, among other factors.

The presented data show that for maximum digestion efficiency the digester must be operated at the maximum sludge age. In this respect UASB design is different from the design of activated sludge systems, in which the minimum sludge age is normally maintained to achieve the goal of the treatment (Van Haandel and Van der Lubbe, 2012). Therefore, the activated sludge system is usually not operated at its maximum, but instead controlled at some desirable value. Unfortunately, knowledge about UASB reactor design is still insufficient to make an a priori estimate of the UASB reactor sludge age that will develop with a particular phase separator design and under specified operational conditions, so it is impossible to foresee the UASB's performance. The maximum sludge age can only be determined a posteriori, when the reactor has been built and is operating. The problem is that the sludge hold-up does not only depend on the phase separator design, but also on the mechanical properties of the sludge that develops, particularly its settling velocity. These properties depend on the operational conditions in the reactor as well as the influent characteristics. It would appear that theory is not yet sufficiently developed to give an estimate of the settling velocity of UASB sludge for sewage treatment. The following empirical expressions were found by trial and error from the data in Tables 1 and 2 or Fig. 4b:

$$mS_e = 0.14 + 0.25^{-0.04(R_S - 6)} \quad (9)$$

$$mS_x = 0.12 + 0.20^{-0.04(R_S - 6)} \quad (10)$$

So that:

$$mS_d = 1 - mS_e - mS_x = 0.74 - 0.45^{-0.04(R_S - 6)} \quad (11)$$

As the expressions of Eqs 9, 10 and 11 were obtained from experimental data (Tables 1 and 2), their validity is restricted to the reactor configurations, operational conditions (average temperature of 25°C) and sewage characteristics during the experimental investigation.

Figure 4(b) is also very useful for an evaluation of the composition of the COD fractions present in the effluent and converted into sludge. Marais and Ekama (1976) divided the influent COD material in a biodegradable and a non-biodegradable fraction, each with a soluble and a particulate component. Thus the COD fractions, f_{us} and f_{up}, are defined as the non-biodegradable influent soluble and particulate COD fractions, respectively. At very long sludge ages, it may be assumed that the biodegradable material is completely used by the bacteria, so that in the effluent only non-biodegradable material persists (top section indicated in Fig. 4b), representing a fraction of $f_{us} = 0.14$. At shorter sludge ages, there is a progressive increase in the presence of biodegradable material in the effluent as well as in the produced sludge. It is interesting to note that methanogenesis remained efficient even for sludge ages as low as 6 days (see Table 1): the average VFA concentration almost always remained below 60 mg/L. Hence the increased biodegradable COD concentration at shorter R_s must be attributed to inefficiency of the processes preceding acetogenesis: hydrolyses and acidogenesis.

On the other hand, in Fig. 4b COD fraction discharged as sludge increases strongly as the sludge age decreases, even though bacterial growth due to anaerobic digestion is reduced. This means that, as the sludge age decreases, an increasing fraction of the influent COD is discharged as flocculated particulate organic material that has not yet been affected by hydrolysis and therefore has not been available for any of the biological processes developing in the UASB reactor. Therefore, at low sludge ages sludge stability may not be in conformity with guidelines or legal norms (USEPA, 1992). The experimental data can be used to estimate the non-biodegradable particulate influent COD fraction and the overall apparent yield factor, as well as the fractions of biodegradable and non-biodegradable (inert) solids and bacterial sludge mass. In Fig. 4b it can be seen that the bacterial mass fraction in the produced sludge at low sludge ages is small compared to the biodegradable fraction. However, at very high sludge ages (200 d) it may be assumed that the biodegradable organic material is largely metabolized and the sludge fraction is then

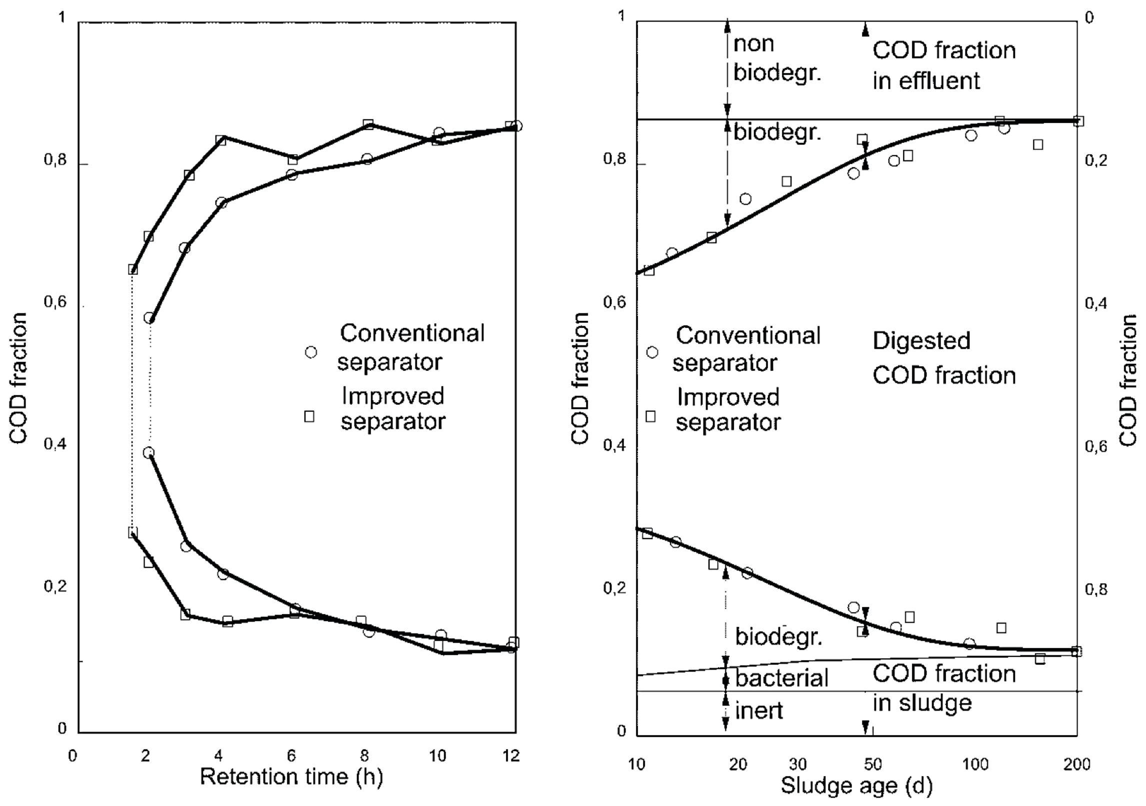

Figure 4

COD fractions in the effluent, in the excess sludge and digested as functions of Rh (left) in Reactors A and B, and Rs (right) in Reactors A and B

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composed of bacterial sludge and inert sludge from non-biodegradable particulate organic material. Under these conditions the fraction of the influent COD that is transformed into bacterial mass can be estimated as follows: digested fraction is equal to:

$$mS_{d,max} = 1 - f_{us} - f_{up} - f_{cv}Y_{ap}$$

$$mS_{x,max} = f_{up} + f_{cv}Y_{ap}mS_{m,max}$$

and:

$$mS_{d,max} = f_{cv}Y_{ap}mS_{m,max}$$

so that:

$$mS_{x,max} = 0.12 = f_{up} + f_{cv}Y_{ap}/(1 - f_{cv}Y_{ap})mS_{d,max} = f_{up} + 1.5 \times Y_{ap}/(1 - 1.5Y_{ap}) \times 0.74 \qquad (12)$$

where:

$mS_{x,max}$ = maximum fraction of the influent COD that is transformed into bacterial mass
$mS_{m,max}$ = maximum fraction of the influent COD that is metabolized in the reactor
$mS_{d,max}$ = maximum fraction of the influent COD that is digested
f = non-biodegradable and particulate COD influent fraction
Y = apparent yield coefficient (all populations)

Equation 12 does not give a solution, since there are two unknowns: f_{up} and Y_{ap}. However, there is evidence (Wentzel et al., 2006, Ikumi et al., 2014) that f_{up} in an anaerobic environment is not very different from f_{up} in an aerobic environment, where it is about f_{up} = 0.08 (Marais and Ekama, 1976) for raw sewage. In that case an estimated value for the apparent yield factor can be calculated: Y_{ap} = 0.05 mgSVS/mgCOD. This value is not unexpected: it is larger than the minimum value for a substrate consisting only of acetate (i.e. with only methanogens), which is 0.02–0.03 mgSVS/mgCOD (Henze and Harremoes, 1983), and the maximum value where all populations develop at their maximum (i.e. a substrate where all processes of anaerobic digestion must fully develop, which is 0.18 mgSVS/mgCOD (Van Haandel and Lettinga, 1994). Hence, the apparent yield coefficient is indicative of a partially hydrolysed influent, as is to be expected, taking into consideration the high temperature on the Borborema Plateau.

CONCLUSIONS

Sludge age is the fundamental parameter with which to describe the performance of the UASB reactor for sewage treatment and, particularly, the division of the influent COD into three fractions: (i) discharged in the effluent, (ii) converted into sludge and (iii) digested to methane. If the sludge age is the same, UASB reactors treating the same sewage at different liquid retention times will tend to have the same effluent quality and sludge production and therefore the same digestion efficiency. The lower the sludge age, the higher are the fractions of the influent COD ending up in the effluent or in the excess sludge.

The effluent COD of an anaerobic reactor is composed of biodegradable and non-biodegradable material. The biodegradable fraction increases as the sludge age decreases.

Sludge production in anaerobic reactors can be divided into three fractions: bacterial sludge, composed of the populations that effect the anaerobic digestion process, inert sludge generated from the non-biodegradable and particulate fraction of the influent COD, and a biodegradable fraction generated from the biodegradable and particulate fraction of the influent COD. The biodegradable fraction increases as the sludge age decreases.

The sludge age is strongly dependent on the efficiency of the sludge retention device of a UASB reactor. The application of parallel plates, in addition to a conventional phase separator, to form a high-rate settler, was shown to be very efficient in enhancing sludge retention and thus increasing sludge age and treatment capacity of a UASB reactor. In this investigation, application of parallel plates in a pilot UASB reactor (plates at 45° with a depth of 0.35 m and with a spacing of 0.07 m) effectively doubled the treatment capacity of the reactor.

The required liquid retention time (and hence the reactor volume) for a particular COD removal efficiency depends on the average sludge concentration in the reactor, which, in turn, is a function of the sludge retention efficiency achieved by the phase separator.

Reduced efficiency of the preparatory processes of hydrolysis, acidogenesis and acetogenesis, rather than methanogenesis itself, is the cause of poor performance of UASB reactors at low sludge ages.

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