Influence of the phase separator design on the performance of the UASB reactor and on excess sludge production

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Abstract
The efficiency of the phase separator in UASB reactors can be increased by placing additional parallel plates above the conventional device, thus forming a high rate settler. From settling theory it can be deducted the performance of the plates improves when the height of the zone with parallel plates increases or the distance between plates and the angle of the plates decreases. In practice the height is limited by the construction cost of the reactor. The distance between the plates must be sufficient for maintenance and the angle to allow the retained sludge to slide readily back into the digestion zone. The experimental data show that indeed the digested COD fraction is greatly increased by adding parallel plates to a UASB reactor. As a consequence, the improved separator opens the possibility of a considerable increase of the applied load to the UASB reactor: Parallel plates used in a pilot scale (1500 l) UASB reactor led to an increase of the treatment capacity by a factor 2. The experimental data also showed that the fundamental operational variable to describe the behaviour of the UASB reactor is in fact the sludge age: at any particular temperature the effluent quality and the quality and quantity of excess sludge will be equal in two UASB reactors, if the sludge age in these is the same.

Key words
Anaerobic wastewater treatment; phase separator design; sludge age; reactor performance; excess sludge production and composition.

INTRODUCTION

The two main conditions for any well performing waste water treatment system are (1) to ensure good contact between the incoming substrate and the sludge mass in the system and (2) to maintain a large sludge mass in the system. In the UASB the contact is assured by the upflow path of the waste water through the sludge blanket (Lettinga et al 1980). In order to maintain a large sludge mass, the UASB reactor has a built-in phase separator, where the solids are retained by settling, so that the effluent is substantially free from settleable solids. The retained sludge particles will end up sliding back into the sludge layer, thus contributing to the maintenance of a large sludge mass in the reactor.

In a UASB reactor the solid retention mechanism the solids retention time or sludge age (R_s) is always longer than the liquid retention time (R_h). The difference becomes larger, as the phase separator is more efficient. In a UASB reactor treating sewage usually the liquid retention time is of the order of 4 to 6 h and the sludge age in the range 20 to 100 d (van Haandel and Lettinga 1993), so that $R_s/R_h \approx 100$ to 250. The sludge mass that can be retained in the reactor is determined by the hydrodynamics, the settling properties of the sludge and in the case of flocculent sludge, by the phase separator design.

The remarkable performance of the UASB reactor as a unit for sewage treatment is due 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 sludge mass present in the reactor is large and this enhances efficient removal of biodegradable organic material. In this paper it will be shown that by improving the phase separator design, the sludge retention increases and efficient treatment becomes feasible at shorter liquid retention times than those in units with a conventional phase separator.

The influence of the phase separator design on UASB reactor performance was evaluated experimentally. COD removal efficiency and sludge production were observed as a functions of the liquid retention time in two reactors with identical dimensions and receiving the same waste water load, but having different phase separator designs. The first one was the conventional UASB separator (prism with an open base, Fig 1a). In the second design (Fig 1b) the separator efficiency is improved by adding to the conventional design a layer with parallel plates, thus forming a high rate settler in the settling zone above the conventional separator. It can be shown that, at least theoretically, the separator of second type can retain sludge flocs much more efficiently than the conventional separator.

The sludge age was identified as the key parameter to describe the UASB performance: Different systems treating the same waste water will have the same effluent quality and the same sludge production independent of the hydraulic retention time, as long as their sludge ages are the same. Unfortunately the influence of the phase separator design on the sludge age is not yet clearly established, so that no general rules can be given to maximise the phase separator efficiency.

SLUDGE RETENTION IN UASB REACTORS WITH DIFFERENT PHASE SEPARATORS

The conventional phase separator divides the reactor volume between a lower digestion zone and an upper settling zone (Fig 1a). Gas-liquid, gas-solid and solid-liquid separation occurs below the prismatic units at the interface of the liquid with the gas chamber. Additional solid-liquid separation takes place in the settling zone above the separator elements: particles with a sufficiently high settling rate will overcome the drag force of the upward liquid flow and eventually will settle on a separator element and, after having built up a layer with enough mass, slide back into the digestion zone.

In the case of the conventional separator the upflow velocity of the liquid is given by:

$$v_u = Q/A_u \qquad (1)$$

where

v_u = liquid velocity in the settling zone

A_u = area of the settling zone in the UASB reactor

Q = sewage flow

If flocculation in the settling zone is not considered, in the conventional reactor, only flocs with a settling velocity larger than the minimum rising velocity of the liquid can be retained. Flocs with a smaller settling rate will be carried by the liquid flow and discharged together with the effluent. Hence the condition for retention of a particular floc is given by:

$$s_c > v_u = Q/A_u \qquad (2)$$

where:

s_c = critical settling velocity for floc retention by the conventional phase separator.

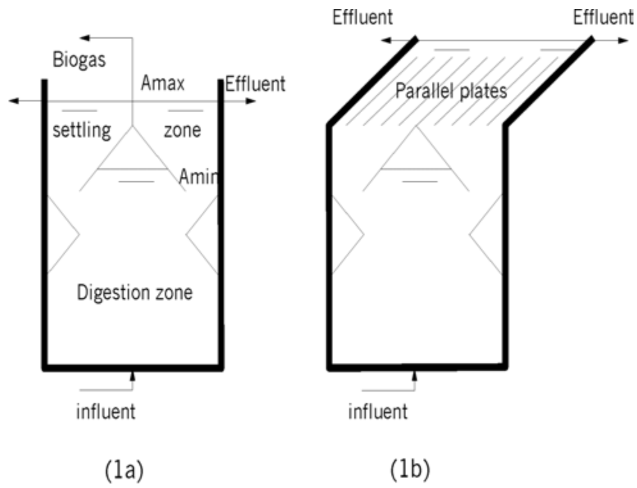


Fig 1: Different designs of phase separators for UASB reactors: (a) Conventional, (b) with parallel plates

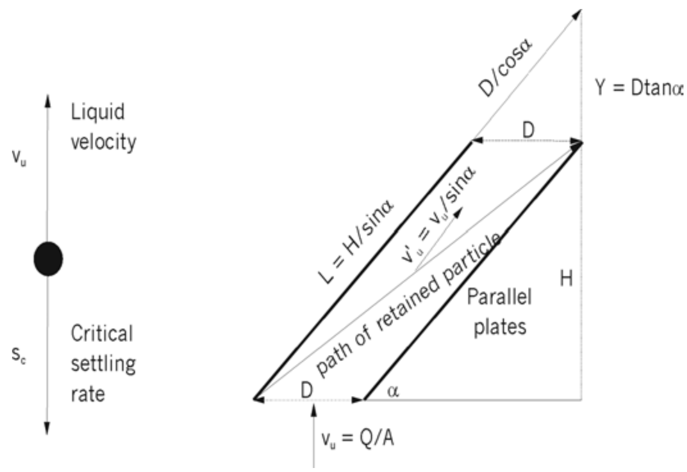


Fig 2: Representation of the settling mechanism for a conventional separator (left) and for a unit with parallel plates (right)

In the alternative design of Fig 1b, the phase separator is composed of two parts. The first part is equal to the conventional separator and effects the separation of the biogas and part of the sludge. In addition there is a second part, composed 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 smaller than the minimum settling velocity for retention in the conventional separator. In Fig. 2 the path of a particle travelling between two plates is indicated: The most unfavourable condition is when a particle enters the plate zone next to the first plate. As the liquid flows through the space between the plates the particle settles and touches the second plate before leaving the plate zone. Such a particle would be retained and eventually be returned to the digestion zone. If the thickness of the plates is neglected the liquid velocity in the space between plates and the critical settling rate are now given as:

$v'_u = v_u/\sin\alpha$ (3)

and

$s'_c > v_u D\tan\alpha/(H/\sin\alpha + D/\cos\alpha)$ (4)

where:

α = angle of the parallel plates;

H = depth of the zone with plates and (m)

D = spacing of the plates.(m)

Hence the ratio of the critical settling velocity in a separator with parallel plates and in a conventional separator is given by:

$s'_c/s_c = D\tan\alpha/(l\sin\alpha + D\tan\alpha) = 1/(L\cos\alpha + 1)$ (5)

where:

L = *l*/D, the ratio between the length and the spacing of the plates

Equation (4) shows that the minimum settling velocity of the flocs that can be retained in the separator with parallel plates is always smaller in the conventional separator. The difference becomes more pronounced as e and α become smaller or L larger. Hence, for a efficient floc retention by the parallel plates one must have: (1) a small distance between the plates (D), (2) a small angle of the plates with the horizon (α) and/or (3) long plates, i.e. a large depth of the zone with plates (H). All three factors above are limited by practical considerations: (1) the distance between the plates cannot be very small to avoid blockages (2) the angle of the plates must have a minimum value to make sure the settled sludge flocs will readily slide back into the digestion zone and (3) for economic reasons the depth of the zone with parallel plates cannot be very large.

Figure 3 shows the ratio s'_c/s_c as a function of the depth of the zone with plates for angles of 45 and 60^o, which represent respectively the minimum and maximum values commonly used for separator elements in UASB reactors. The ratios are calculated for three different distances between the plates: D = 0,1; 0,2 and 0,3 m. From Fig 3 it is concluded that for practical values of D, α and H, theory predicts a large difference between the settling velocities of particles that can be retained in the reactor with parallel plates and in the conventional UASB reactor. Equivalently, it is possible to increase the hydraulic load in a reactor with parallel plates and yet have the same efficiency of floc retention as in the case of the reactor with a conventional separator. It is important to note that it is **not** possible to increase the sewage flow proportionally, because then also the organic load (and consequently the sludge production) would increase. In Fig 2b it can be seen that for the same spacing and depth the s'_c/s_c for plates with 60^o is smaller than for those with 45^o, but on the other hand the settled sludge will slide more easily back into the digestion zone.

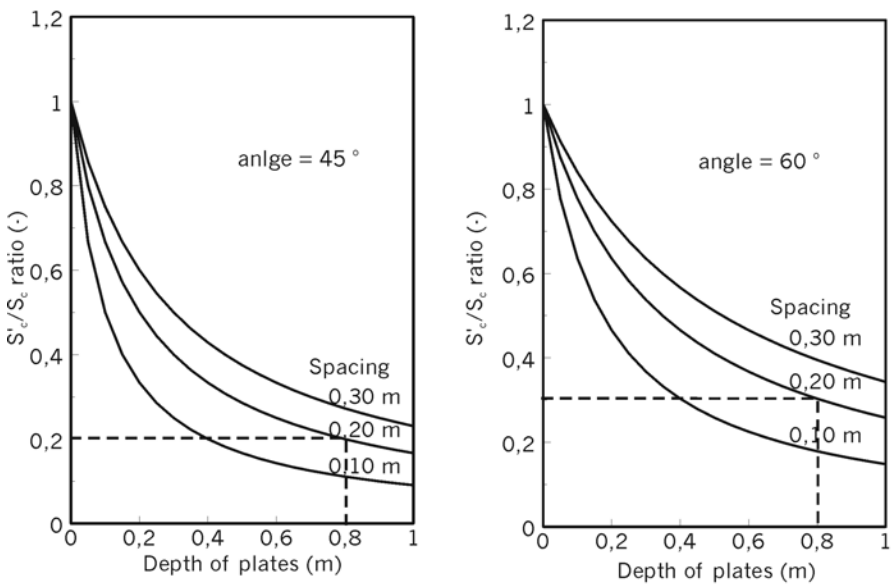
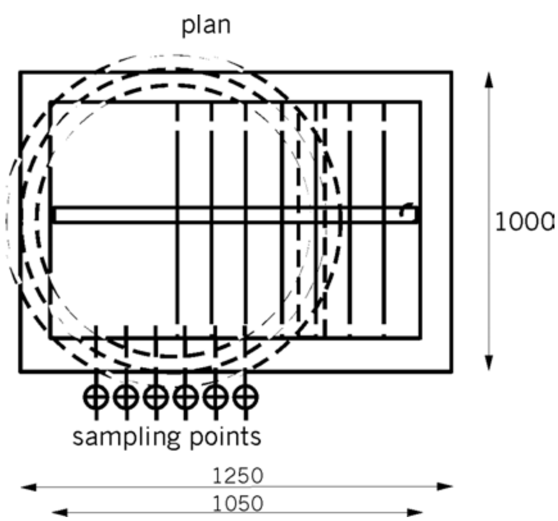


Fig 3: Ratio between the critical settling velocities of flocs in UASB reactors having a separator with parallel plates (Fig 1b) and having a conventional separator (Fig 1a) as a function of the depth of the parallel plate zone for different spacings and angles.

EXPERIMENTAL INVESTIGATION AND RESULTS

An experimental investigation was carried out at pilot scale, to evaluate the effect of the phase separator design on the performance of the UASB reactor. Raw sewage of the city of Campina Grande (Brazil) was used as influent. Two pilot scale UASB reactors were used with the same physical dimensions, the difference being that the first unit (A) had a conventional phase separator, while the second (B) had parallel plates in addition to the conventional separator. The plate zone was H = 0,35 m high and the angle was α = 45 ^{o}, so that the length was l = 0,50 m. The spacing between the plates was 0,07 m. Figure 4 shows a sketch of reactor B. The reactors were operated under identical operational conditions and retention times were varied from 12 to 1,5 h. After establishing a particular retention time, the reactor was operated for a period of not less than 1 month before the experimental data were used for calculations. Both reactors were operated without intentional discharge of excess sludge, so that the maximum sludge mass was built up, where after sludge was expelled at the same rate it was produced in the reactor. The reactors were operated at constant flow rates and experimental data were obtained after the maximum sludge hold-up had been established for each of the investigated retention times. It was considered that any particles settled in an Imhoff cone during 30 min were sludge particles and that the supernatant COD of the cone was the true effluent COD. For this reason, both the raw and settled effluent CODs were determined. The difference of the two effluent CODs was used to estimate the volatile 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 1,5 g, (Ekama and Marais, 1976) the effluent volatile sludge concentration was calculated as:



$X_{ve} = (S_{re} – S_{se})/1,5$

where:

X_{ve} = concentration of volatile sludge in the effluent

S_{re} = raw effluent COD concentration

S_{se} = settled effluent COD concentration

For the conditions in Campina Grande (sewage alkalinity of 350 ppm CaCO3, COD concentration < 1000 mg/l, temperature >25 oC) the buffer index of the sewage was always sufficient to maintain the pH in the neutral range (6,8 to 7,1). On the other hand methanogenesis was always efficient and the volatile acids concentration never exceeded 1 mmol/l (60 mg/l HAc) and usually was less than 0,5 mmol/l. This was true for both the conventional UASB reactor and the unit with the improved separator and for the entire range of investigated retention times. As a consequence the operational stability was excellent throughout the investigation and there was no danger of souring of the UASB reactors at any stage.

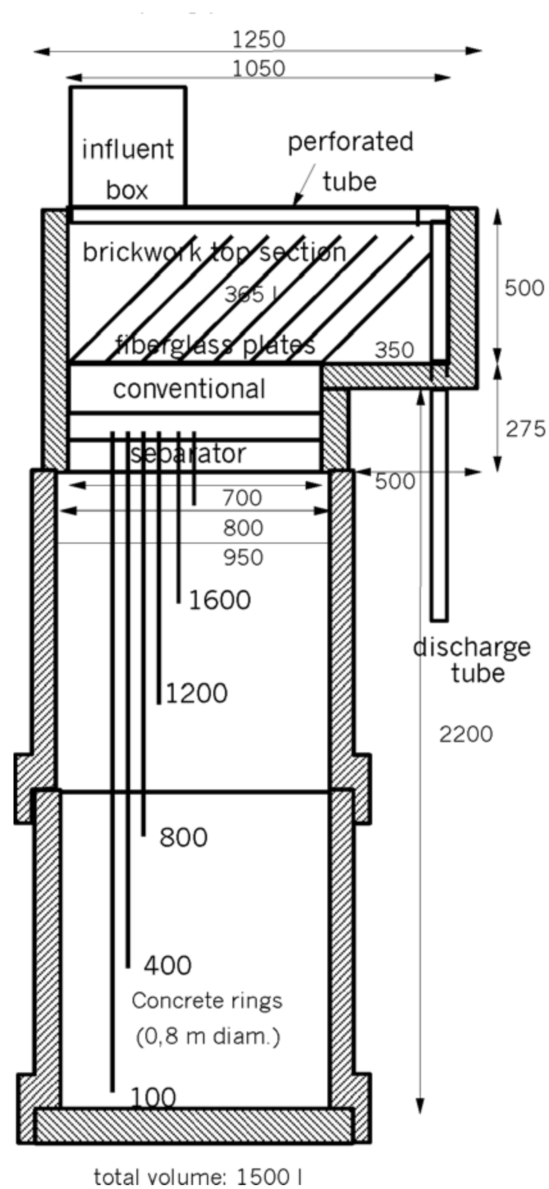


Fig 4: Representation of the l UASB reactor used in the experimental investigation (values in mm).

Table 1: Effluent COD concentrations (raw and settled) for different retention times in the conventional UASB reactor (A) and the unit with an improved phase separator (B)

R_u (h)	COD concentration					Sludge mass, composition and age					
		Reactor A		Reactor B		Reactor A			Reactor B		
	Raw Infl.	Raw Effl.	Sett. Effl.	Raw Effl	Sett. Effl	gTSS/l	Vol.fr	R_s	gTSS/l	Vol.fr	R_s
12	587	157	88	147	72	20,6	0,54	122	36,6	0,56	205
10	492	143	78	128	59	18,0	0,57	98	29,7	0,58	155
8	554	189	108	158	94	16,1	0,58	58	37,0	0,61	120
6	480	186	102	133	67	16,0	0,61	44	19,7	0,57	64
4	526	252	133	185	93	17,5	0,65	21	28,2	0,61	47
3	619	360	195	210	106	16,9	0,67	13	35,6	0,61	39
2	561	454	236	264	154	14,6	0,68	6	23,7	0,63	17
1,5	613			407	214				28,8	0,68	11

Table 1 shows that influent COD concentrations as well as the raw and settled effluent values for units A and B for the different retention times. In the same table the sludge mass and composition (average concentration and volatile fraction) are also presented. The sludge mass (total and organic) was determined from linearized profiles, using the sludge concentrations at the sample points (Fig 4). The sludge production was estimated from the difference between the values of the raw and settled effluent COD concentrations. The sludge age was calculated as the ratio between the volatile sludge mass in the reactor and the daily production found in the effluent (Eq 6).

DISCUSSION

The data show that the average sludge concentration in reactor B (with the parallel plates) was much larger than in reactor B with the conventional separator. This must be attributed to the retention of very small flocs on the parallel plates. When these are deposited, the physical contact they make apparently is sufficient for the formation of larger and mechanically stable flocs that slide back into the digestion zone where they contribute to the removal of organic material from the liquid phase.

In the UASB reactor the influent COD (S_{ti}) is divided into three fractions (1) mS_{eu}, organic material in the effluent (2) mS_{vu}, organic material transformed into sludge and (3) mS_{du}, digested organic material. The objective of the anaerobic treatment is that the first two fractions be minimum and the third maximum. The first two fractions can be calculated from that data in Table 1, and the third can be calculated by subtraction these two fraction from unity:

$mS_{eu} = S_{se}/S_{ti}$

$mS_{xu} = (S_{re} - S_{se})/S_{ti}$

$mS_{du} = 1 - mS_{eu} - mS_{vu}$

In Fig 5a the experimental values of mS_{eu} and mS_{vu} are shown for reactors A and B for the applied liquid retention times On the basis of the experimental data empirical curves were drawn for the organic material fractions as a function of the retention time for reactor A (interrupted curve) and B(drawn curve). Clearly both the fractions mS_{eu} and mS_{vu} increase, as the retention time decreases, which is contrary to the objective of the anaerobic treatment, where these fractions must be minimum. The curves indicate a very strong influence of the phase separator on the performance of UASB reactor. For the same digested COD fraction the required retention time in reactor B is about half the value required in reactor A. Hence the parallel plates in reactor A led to a doubling of its treatment capacity.

The data in Table 1 can also be used to plot the three COD fractions as functions of the sludge age as shown in Fig 5b. If the sludge age is used as the independent variable, the COD fractions mS_{eu} and mS_{vu} in reactors A and B in good approximation can be described with a single curve. This means that for any particular sludge age the fraction of the influent COD ending up in the effluent or converted into sludge is always the same, independent of the phase separator design or the liquid retention time that is applied. It is concluded that the sludge age and not the liquid retention time is the relevant parameter to describe the behaviour of the UASB reactor for sewage treatment. Fig 5b also shows that there is a minimum sludge age below, which no methanogenisis takes place and all the organic material leaves the reactor either in the effluent or as flocculated material in the excess sludge.

The deterioration of UASB reactor performance at decreasing retention times must be attributed to the increasing fraction of biodegradable organic material of the influent that is not digested in the reactor. In Fig 5b it can be seen that for a very long sludge age the settled effluent COD tends to a constant value, which is identified as the non-biodegradable soluble fraction of the influent COD. The increasing effluent COD at shorter sludge ages indicates that a growing fraction of the influent biodegradable material leaves the reactor as soluble material, though not only VFA, because their concentration hardly increases. It is concluded that at shorter sludge ages there is an increasing inability of the sludge to perform efficiently the acidogenic fermentation of hydrolysed material. Similarly, as indicated in Fig 5b, at very long sludge ages the sludge production is minimum and composed of non-biodegradable particulate influent material and bacterial sludge. At shorter sludge ages there is a decrease of the

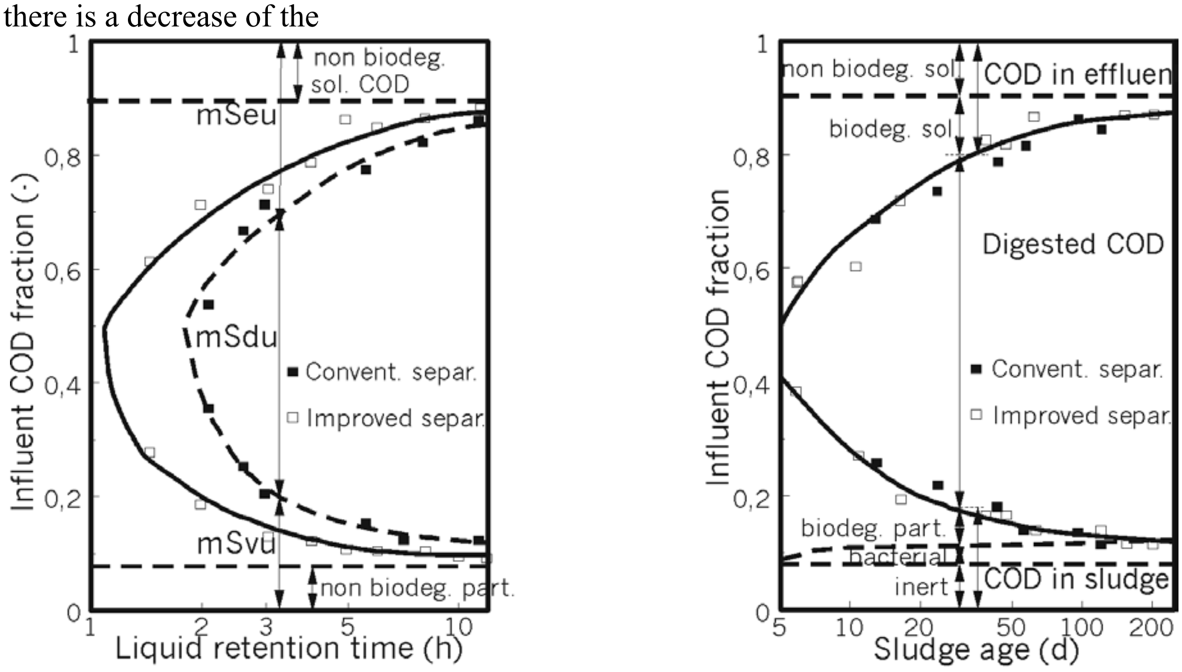


Fig 5a: COD fractions in the effluent, in the excess sludge and digested in UASB reactors with a conventional and an improved phase separator as a function of the hydraulic retention time (log scale).

Fig 5b: COD fractions in the effluent, in the sludge and digested in UASB reactors with a conventional and an improved phase separator as a function of the sludge age (log scale).

bacterial sludge production (less organic material is digested) but the COD fraction converted into sludge increases which can only be attributed to the presence of biodegradable particulate influent COD. It is concluded that the increased fraction of the influent COD that is converted into sludge must be attributed to inefficiency in the hydrolytic process itself.

Unfortunately knowledge about UASB reactor design is still insufficient to make an *a priori* estimate of the sludge age UASB reactor with a particular phase separator design will have under specified operational conditions. This parameter can only be determined when the reactor is operating. The sludge hold-up does not only depend on the phase separator design, but also on the mechanical properties of the sludge, particularly the settling velocity and on mixing intensity (gas bubbles).

Once the sludge age has been identified it is interesting to express the COD fractions mS_{eu} and mS_{vu} as a function of this parameter. By trial and error the following empirical expressions were found:

$mS_{eu} = 0,14 + 0,32exp(-0,04(R_s-4)$ (7a)

$mS_{vu} = 0,12+0,25Exp(-0,04R_s-4)$ (7b)

so that

$mS_{du} = 1=-mS_{eu}-mS_{vu} = 0,74 - 0,57exp(0,04R_s-4)$ (7c)

CONCLUSIONS

(1) The sludge age is the fundamental parameter to describe the performance of the UASB reactor for sewage treatment and particularly the division of the influent COD into three fractions: (1) discharged in the effluent, (2) converted into sludge and (3) digested to methane.

(2) Reduced efficiency of the preparatory processes of hydrolysis, acidogenisis and acetogenisis rather than methanogenisis itself are the cause of poor performance at short sludge ages

(3) The sludge age is strongly dependent on the efficiency of the sludge retention device of a UASB reactor. The application of parallel plates to form a high rate settler is extremely efficient.

(4) The required hydraulic retention time (and hence the reactor volume) determines the average sludge concentration in the reactor, which is also a function of the sludge retention efficiency by the phase separator.

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