Effects of a recycle in upflow anaerobic sludge bed (UASB) systems

PALNS Sam-Soon, RE Loewenthal, MC Wentzel, RE Moosbrugger and GvR Marais*
Department of Civil Engineering, University of Cape Town, Rondebosch 7700, South Africa.

Abstract

Two major problems arise in the operation of UASB systems treating carbohydrate wastes; high influent CODs and inadequate influent alkalinity/influent COD. These cause the minimum pH in the bed to decline below 6,6 which can lead to failure of the system. This paper investigates the use of a recycle from the effluent to the influent to reduce the influent alkalinity requirements per influent COD, and to reduce the effective influent COD concentration. In flow through systems treating a carbohydrate waste, minimum influent alkalinity requirement is about 1,2 mg (as $CaCO_3$)/mg influent COD. The minimum influent alkalinity requirement can be reduced by imposing a recycle, the reduced requirement given by 1,2 x base flow/(base + recycle flow) mg alkalinity (as $CaCO_3$)/mg influent COD. The effective influent COD concentration is correspondingly reduced. At or near the maximum sludge loading rate the recycle may have an adverse effect on system performance; it interactively increases the loading rate above the maximum by recycling short-chain fatty acids and COD that "leak" through the sludge bed. Guidelines to determine the maximum loading rate are given.

Introduction

In the pH profile up the sludge bed of a UASB reactor treating apple juicing waste water, characteristically the pH commenced to decline from the influent entry at the bottom to a minimum at the point in the bed where the concentrations of short-chain fatty acids (SCFA), acetate and propionate, attained maxima (Sam-Soon *et al.*, 1987). Thereafter the pH increased monotonically to some stable value in the upper part of the bed. When the minimum pH declined to below about 6,6, the overall COD removal efficiency decreased and the SCFA concentrations in the upper part of the bed increased - the system showed signs of incipient failure.

To limit the pH decline, alkalinity was added to the influent. For the apple juicing waste water, a carbohydrate waste with zero alkalinity, it was found by trial that the addition of about 1,6 mg alkalinity (as $CaCO_3$)/mg influent COD (by addition of $NaHCO_3$) maintained the minimum pH above 6,6. In full-scale plant operation provision of alkalinity of this magnitude would incur significant operational costs.

In a normal functioning completely mixed anaerobic fermentation system treating a carbohydrate waste **the net alkalinity consumption is virtually zero.** The reason for this is that in order to generated, so that from this source there is virtually no net acidity low hydrogen partial pressure (by having completely mixed conditions and low average organic loading per unit mass of sludge), and as a consequence very little or no SCFA are present in the reactor -the only SCFA generated is acetic acid due to the low hydrogen partial pressure, and this is converted to methane at the rate generated, so that from this source there is virtually no net acidity generated and, hence, very little or no alkalinity supplementation is required to maintain a near neutral pH. The only other source of acidity gain/alkalinity loss is the conversion of free and saline ammonia (NH_3/NH_4^+ form) to organic nitrogen (in the $NH/NH_2/NH_3^+$ form) for sludge production; this is also relatively minor. In the treatment of proteinaceous wastes there is an **increase** in alkalinity/loss of acidity from influent to effluent due to breakdown of proteins ($NH/NH_2/NH_3^+$ form) to free and saline ammonia (NH_3/NH_4^+ form). With short-chain fatty acids in the influent there is a **reduction in acidity** in their conversion to methane. Accordingly, for most waste waters **in completely mixed anaerobic** systems little or no alkalinity supplementation is necessary to maintain the pH above 6,6.

In semi-plug or plug flow anaerobic systems treating carbohydrate wastes the situation may be quite different from that in completely mixed systems. In a UASB system, for example, treating a carbohydrate waste, first there is a net loss of alkalinity (and a net gain of acidity) due to a substantial removal of NH_3/NH_4^+ by conversion to organic nitrogen for pelletised bed formation and second, in the pelletised bed there is a partial phase separation of acidogenesis and methanogenesis giving rise to a build-up of SCFA in the lower active (high hydrogen partial pressure, high $\bar{p}H_2$) zone of the bed (Sam-Soon *et al.*, 1990a); the SCFA generated increase acidity and reduce alkalinity. In this zone the combined nitrogen and SCFA effects cause a drop in pH. In the upper active (low $\bar{p}H_2$) zone of the bed the SCFA are converted to methane; there is a net decrease in acidity causing an increase in pH. The overall effect from influent to effluent is a relatively small net alkalinity loss in the system. Thus the function of alkalinity is principally to control the pH decline in the high $\bar{p}H_2$ zone - alkalinity supplementation in the influent in effect eventually is wasted in the effluent.

The same pH response described above had been noted by Young and McCarty (1967) in their study of upflow anaerobic filters, a decline in pH at the bottom of the filter bed and subsequent recovery of pH in the upper part. These filters were operated as plug flow systems and, as in UASB systems, there was a partial phase separation of acidogenesis and methanogenesis. They also had observed a reduction in COD removal efficiency when the minimum pH declined to about 6,2. In these respects the filter and UASB systems appear to behave in a similar fashion.

With protein-carbohydrate wastes, Young and McCarty (1967) found that alkalinity supplementation of 0,5 to 1 mg alkalinity (as $CaCO_3$)/mg influent COD was sufficient to maintain the pH above 6,6. This alkalinity requirement is smaller than that found necessary in the UASB system treating apple juicing waste water (1,2 to 1,6 mg alkalinity (as $CaCO_3$)/mgCOD influent, Sam-Soon *et al.*, 1987). Most likely the lower alkalinity requirement was due to internal production of alkalinity when NH_3/NH_4^+ was generated during deamination of the proteinaceous component of the waste.

Capri (1973), when studying upflow anaerobic filters treating strong spent wine wastes (COD ≈ 23 000 mg/ℓ), countered the

---

*To whom all correspondence should be addressed.

Received 12 March 1990; accepted in revised form 11 June 1990.

decline of pH by instituting a very high recycle ratio (recycle ratio ≈ 35:1) without alkalinity supplementation. By this means the pH in the filter could be kept near 7 throughout the filter which allowed treatment of the waste up to 4 kgCOD/m^3 reactor volume.d. He noted that a lower recycle ratio also might have been adequate. Cronje (1973), investigating fermentation of glucose-starch wastes in an upflow anaerobic filter with influent COD ≈ 7 000 mg/ℓ, observed a decline in pH in the lower region of the filter, and found that the magnitude of decline could be reduced by imposing a recycle. Relatively low recycle ratios of 0,9:1 were sufficient to control the minimum pH in the filter to 6,4 at the highest loading (≈ 5 kgCOD/m^3 reactor volume.d). (At loading > 4 kgCOD/m^3 reactor volume.d, Cronje (1973) observed a massive increase in VSS production that caused extensive blockage in the filter and channeling. In the light of our present understanding his filter was commencing to form pellets).

The success achieved in pH control by instituting a recycle on the filters raised the question whether, in UASB systems, recycling also would act as a pH control measure and reduce the alkalinity requirement. However, whereas in the filter system the objective was only to maintain pH above 6,6, in the UASB system a minimum pH ≥ 6,6 would be required without disrupting pelletisation in the high $\bar{p}H_2$ zone. No quantative information was available on the effect of the recycle on the system response, in particular on pellet formation in the high $\bar{p}H_2$ zone.

This paper reports a study on the effect of a recycle on the response of a UASB system with apple concentrate substrate at 30°C.

Experimental

A single UASB reactor system, identical to that described by Sam-Soon *et al.* (1987), was set up with reactor volume of 9 ℓ (see Fig. 1). For the purpose of this investigation the sludge bed volume was set at 3 ℓ and maintained by wasting daily the volume of pellets in excess of 3 ℓ; experience with this system (Sam-Soon *et al.*, 1987) had shown that with this sludge mass the biological reactions would be complete well before the top of the sludge bed for loading rates up to about 44 kgCOD/m^3 sludge bed volume.d. The substrate was apple juice concentrate, suitably diluted to the influent concentration to be tested and supplemented with nutrients and trace metals, as described by Sam-Soon *et al.* (1987). Nitrogen in NH_3-N form was added in excess, 0,0334 mg(NH_3-N)/mg influent COD. (Sam-Soon *et al.* (1990b) concluded that for a carbohydrate waste the minimum nitrogen/COD ratio should be about 0,017 to 0,02 mgNH_3-N/mg influent COD to prevent inhibition in pellet formation). The influent pH ≈ 4,6 and the influent alkalinity (more precisely the $H_2CO_3^*$ /NH_4^+ / $H_2PO_4^-$ /HAc/HPr alkalinity; see below and Loewenthal *et al.*, 1989) was near zero.

To investigate the effects of a recycle on system response, the UASB reactor system was operated at a temperature of 30°C, the temperature was controlled by wrapping around the reactor a heating element connected to an electronic control box with a temperature sensor. Where a recycle stream was instituted, it was taken from the region above the bed at the sample port closest to the settler so that no pelletised sludge was recycled (Fig. 1). The recycle flow joined the influent feed flow approximately 850 mm upstream of the point where the combined stream entered the bottom of the reactor. Even at the largest recycle ratio (3:1), no fluidisation of the sludge bed was evident. For each experiment with the UASB reactor system, after steady state had been established, profiles of COD, TKN, free and saline ammonia (NH_3-N), organic nitrogen (orgN), propionic and acetic acids (HPr and HAc), pH and alkalinity were taken up the bed. COD, TKN, NH_3-N and orgN were measured according to Standard Methods (1985). HPr and HAc were measured using a Packard 417 gas chromatograph fitted with a 6 ft x 1/8" GP 10% SP-1200 (1% H_3PO_4) on 89/100 Chromasorb WAW glass column. The pH was measured by drawing samples directly into a sealed chamber with a fitted pH probe. The alkalinity measured was the $H_2CO_3^*$ /NH_4^+ /$H_2PO_4^-$ /HAc/HPr alkalinity, that is, it included the alkalinity contributions of all the weak acid/base systems with respect to their respective reference species in the alkalinity designation above (Loewenthal *et al.*, 1989). The measurements were done using the modified Gran titration for mixtures of weak acid/base systems, as described by Loewenthal *et al.* (1989). No biogas volume measurements were taken due to failure of the gas meter.

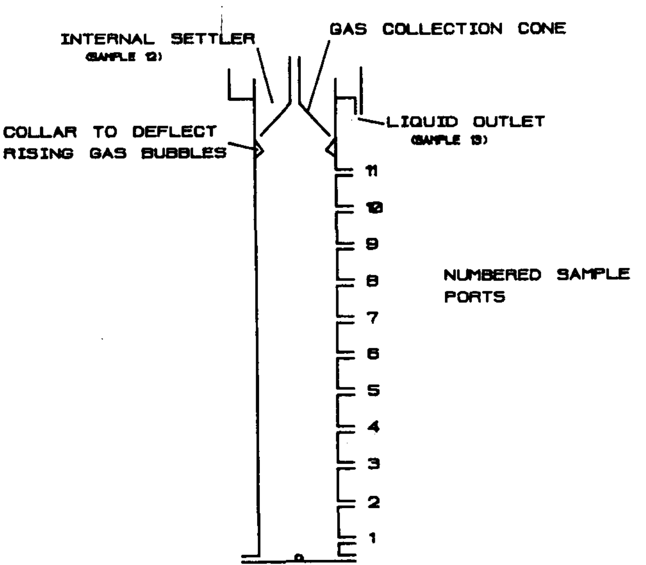


Figure 1
Schematic diagram of the laboratory-scale UASB reactor showing the numbered sampling ports (internal diameter = 100 mm, height to port 11 = 950 mm). Where a recycle was included, it was drawn from sampling port No. 11 and returned to the influent flow line at a point 850 mm upstream from the reactor.

Results and discussion

Recycle at loadings less than maximum

The first series of experiments was orientated to studying the behaviour of a UASB system with and without a recycle when operated at loading rates well below the maximum previously observed by Sam-Soon *et al.* (1987), i.e. maximum of ± 44 kgCOD/m^3 sludge bed volume.d on a 3 ℓ bed volume. The loading rate selected was 28,5 kgCOD/m^3 sludge bed volume.d (influent flow = 30 ℓ/d; COD = 2 850 mg/ℓ) and the alkalinity supplemented with 1,6 mg alkalinity/mg influent COD (henceforth described as 1,6 Alk/COD for convenience), by adding $NaHCO_3$. For the system without a recycle, the mean inputs and responses (minimum pH, percentage removal of COD) are listed in Table 1, Exp. A1. Profiles for the system without a recycle are shown in

TABLE 1
PROCESS SPECIFICATIONS AND RESPONSES FOR A SINGLE UASB SYSTEM WITH APPLE JUICE SUBSTRATE (TEMPERATURE: 30°C)

Exp No.	Flow rate ℓ/d	Average Influent COD mg/ℓ	Loading kgCOD/m³ Sludge bed volume.d	Recycle ratio	Alkalinity addition per mgCOD influent mgAlk (as $CaCO_3$) /mgCOD	Effective* alkalinity mgAlk (as $CaCO_3$) /mgCOD inf.	Overall COD removal %	Minimum pH
A1	30	2 850	28,5	0:1	1,60	1,60	96	6,71
A2	30	2 850	28,5	1:1	1,60	3,20	97	7,01
B1	15	5 700	28,5	0:1	1,20	1,20	96	6,62
B2	15	5 700	28,5	1:1	0,71	1,42	98	6,80
B3	15	5 700	28,5	2:1	0,68	2,04	98	6,82
C1	15	8 500	42,6	0:1	1,22	1,22	92	6,74
C2	15	8 500	42,6	1:1	0,71	1,42	96	6,81
C3	15	8 500	42,6	2:1	0,45	1,35	96	6,82
C4	15	8 500	42,6	3:1	0,46	1,84	92	6,81

$$\text{*Effective alkalinity} = \frac{(\text{Base infl Alk x base flow}) + (\text{effl Alk x recycle flow})}{(\text{base flow + recycle flow})}$$

Fig. 2 (a), (b) and (c). From Table 1 (Exp. A1) and Fig. 2, the minimum pH in the profile for the system without a recycle was 6,7. Thus, alkalinity supplementation of Alk/COD = 1,6, by addition of $NaHCO_3$, was sufficient in this system to maintain the minimum pH $\geq$ 6,6.

A recycle of 1:1 was now imposed upon the system (Exp. A2, Table 1). Profiles of the response are shown in Fig. 3 (a), (b) and (c). The minimum pH increased from 6,7 to 7,0. The alkalinity concentration in the effluent remained approximately the same as the concentration in the base influent flow. Thus the alkalinity concentration of the combined flow (influent flow + recycle flow) was virtually equal to that in the base influent flow but the mass of alkalinity in the combined flow now was twice the mass in the base flow giving rise to an effective influent Alk/COD of 3,2.

Comparing the two sets of profiles (Figs. 2 and 3), the SCFA concentration profiles were reduced to slightly less than half their former values; this was due to the diluting effect of the combined flow. However, the SCFA fluxes (i.e. flow x concentration) at the maximum (sample port No. 1) for both systems remained approximately equal. In the lower active zone of the recycle system the minimum reactor pH also increased because the alkalinity/SCFA ratio had increased. In the upper active zone where the SCFA in both systems had been reduced virtually to zero, the pHs in both systems were nearly identical because the alkalinity concentrations were the same.

From this experiment it was concluded that alkalinity requirement per influent COD could be reduced by recycling from the effluent to the influent.

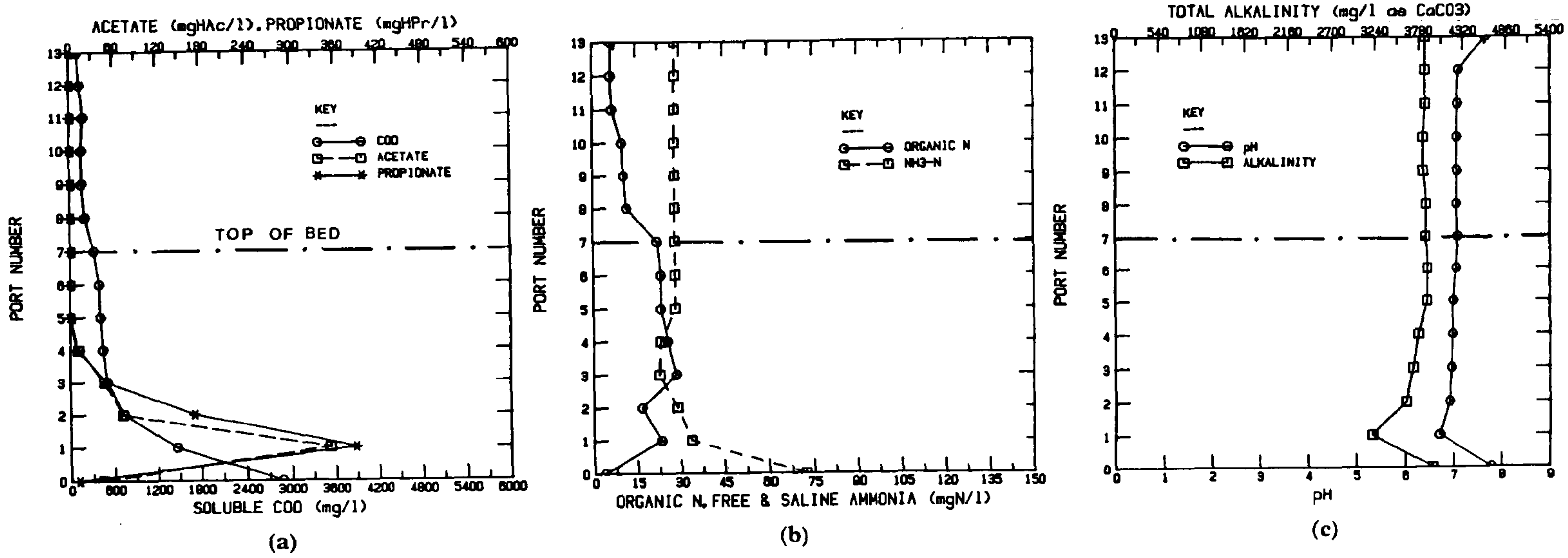
A problem noted with the experiment above was that peak propionate and acetate values were measured at port No. 1, but this did not imply that the true peaks could not have occurred below the level of port No. 1. In an attempt to raise the peaks to above port No. 1, the loading rate was kept constant at 28,5 kgCOD/m³ sludge bed volume.d, but the influent COD concentration was doubled, to 5 700 mgCOD/ℓ, and the flow rate halved, to 15 ℓ/d. At the same time the Alk/COD supplementation ratio was reduced from 1,6 to 1,2 mg alkalinity (as $CaCO_3$)/mg influent COD and the recycle removed, Exp. B1, Table 1. Grab samples at port Nos. 1, 2 and 3 indicated that the peak propionate and acetate values now occurred between port No. 1 and 2.

System response gave minimum bed pH 6,6, COD removal 96 per cent and effluent SCFA 10 mgHAc/ℓ and zero HPr/ℓ. The minimum pH value (6,6) is the lower conventionally accepted value to maintain high hydrogenotrophic process efficiency. Thus, an Alk/COD = 1,2 appeared to be about the minimum ratio on a flow-through system to satisfy pH $\geq$ 6,6 and to give a high COD removal and low SCFA in the effluent.

A recycle of 1:1 was now imposed on the system above but the Alk/COD was reduced to 0,71 to give an effective Alk/COD of 1,42 (Exp. B2, Table 1). The minimum pH increased to 6,8, COD removal to 98 per cent and HAc and HPr concentrations declined to near zero. Clearly a base Alk/COD of 0,71 with a recycle ratio of 1:1 (to give an effective Alk/COD of 1,42) was more than adequate to maintain pH $\geq$ 6,6 and to give excellent COD removal; see profile in Fig. 4 (a), (b) and (c). Indeed the COD removal of 98 per cent was the maximum achieved. To check if further increase in recycle ratio would affect the system, the recycle ratio was increased to 2:1 with the Alk/COD supplementation ratio remaining approximately the same, i.e. Alk/COD = 0,68 (Exp. B3, Table 1). This gave an effective Alk/COD of (2+1) x 0,68 = 2,04. The minimum bed pH and COD removal remained constant, at 6,8 and 98 per cent respectively; profiles are shown in Fig. 5 (a), (b) and (c).

From the experiments above, on systems with loading rates of about 2/3 of the maximum, one may conclude the following:

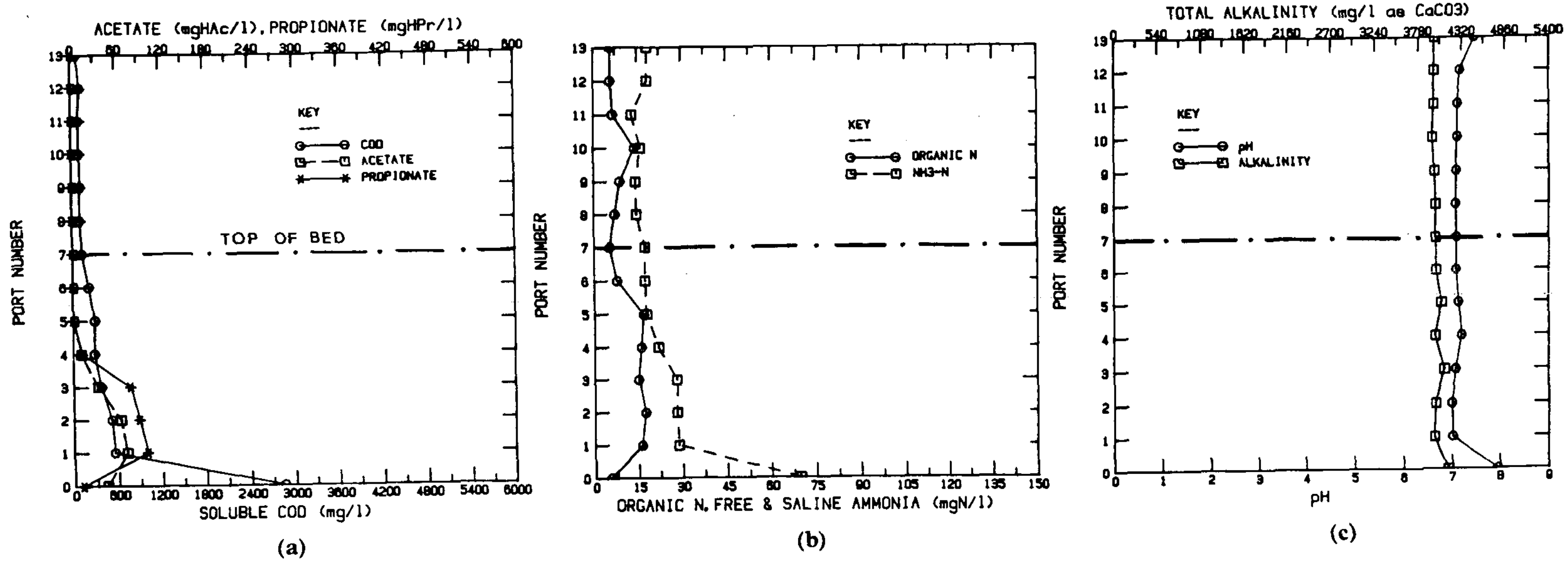
- In a flow-through system the minimum Alk/COD requirement was about 1,2 mg alkalinity (as $CaCO_3$)/mg influent COD in order to maintain the pH $\geq$ 6,6. At smaller Alk/COD ratios the minimum pH would drop below 6,6 and the system would show signs of failure.
- Imposing a recycle from the effluent to the influent was equivalent to increasing the Alk/COD ratio. The effluent alkalinity concentration $\approx$ influent alkalinity concentration, hence the effective Alk/COD ratio, could be determined from:



(a) (b) (c)

Figure 2

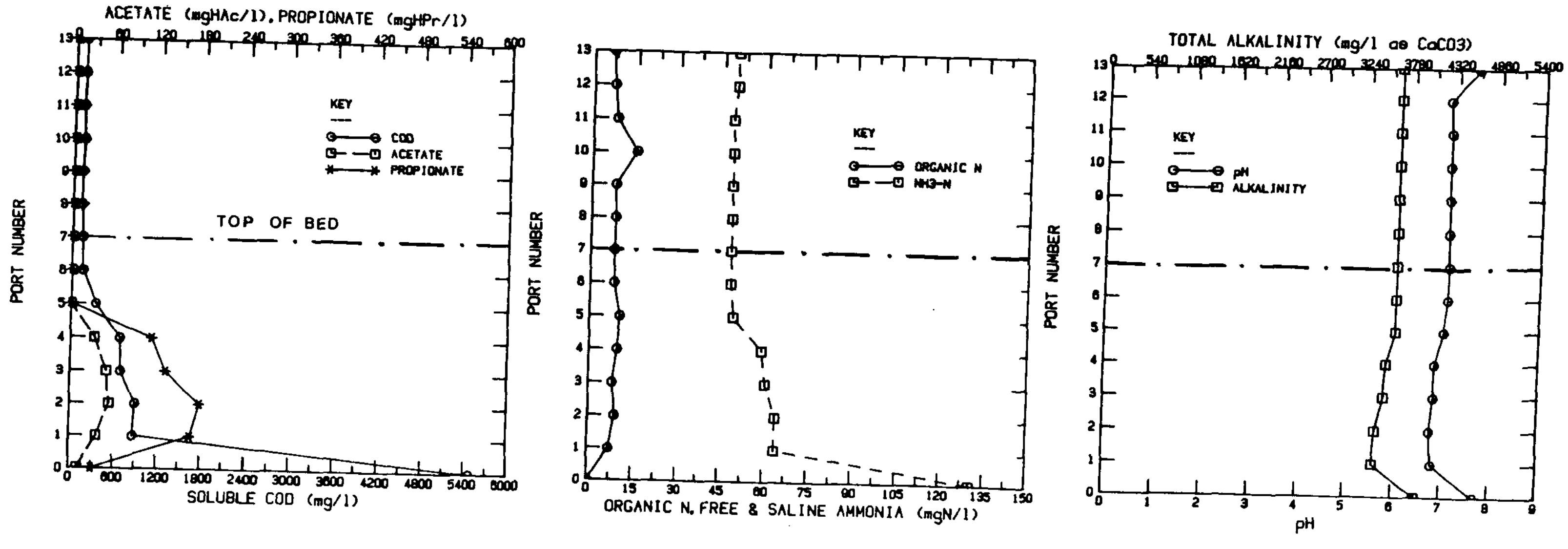
Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 2 850 mg/ℓ; flow rate = 30 ℓ/d; recycle ratio = 0:1; Table 1, Exp. A1)



(a) (b) (c)

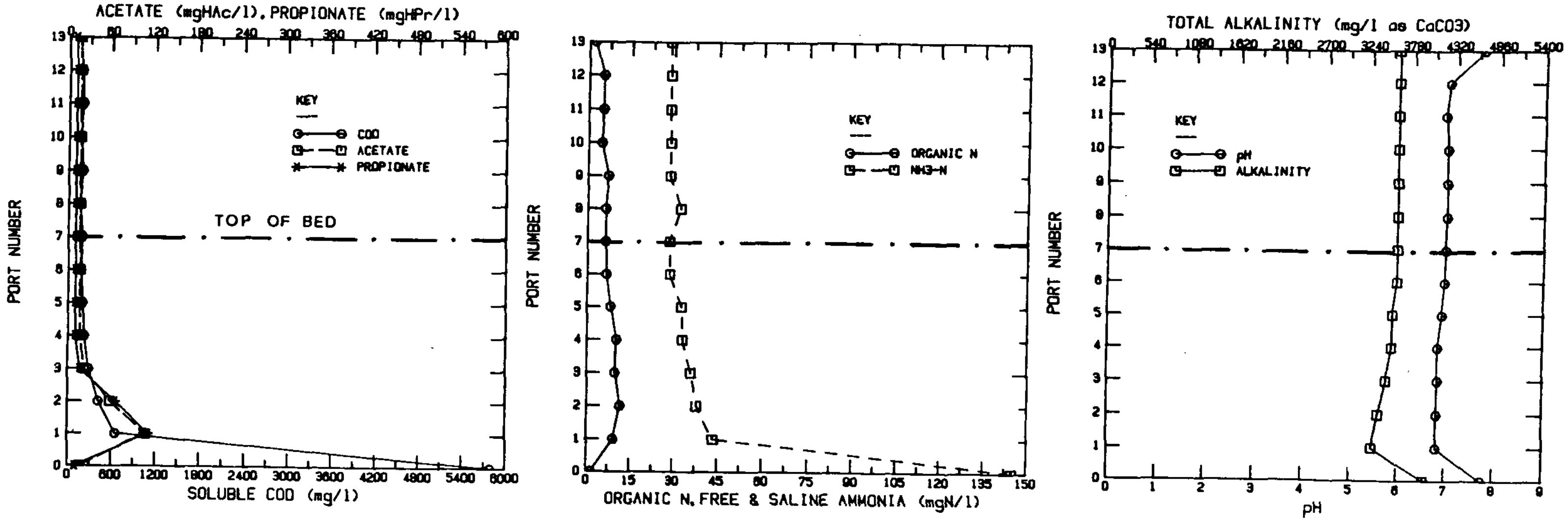
Figure 3

Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 2 850 mg/ℓ; flow rate = 30 ℓ/d; recycle ratio = 1:1; Table 1, Exp. A2)



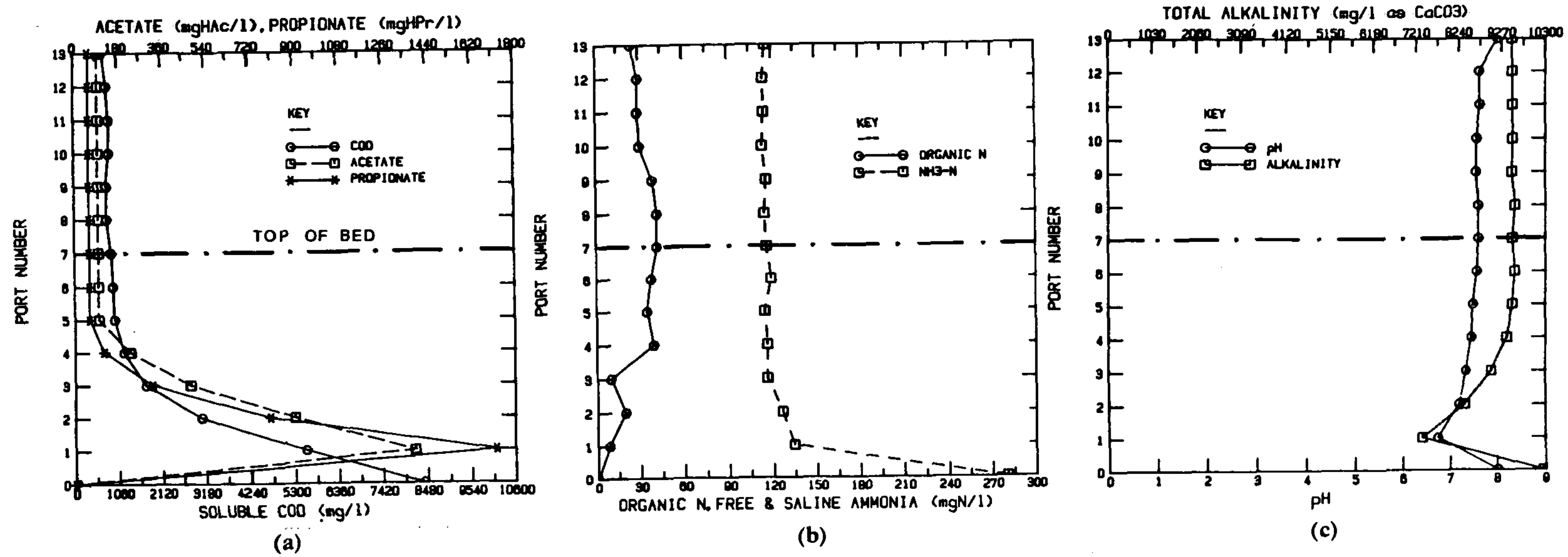
(a) (b) (c)

Figure 4
Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 5 700 mg/ℓ; flow rate = 15 ℓ/d; recycle ratio = 1:1; Table 1, Exp. B2)



(a) (b) (c)

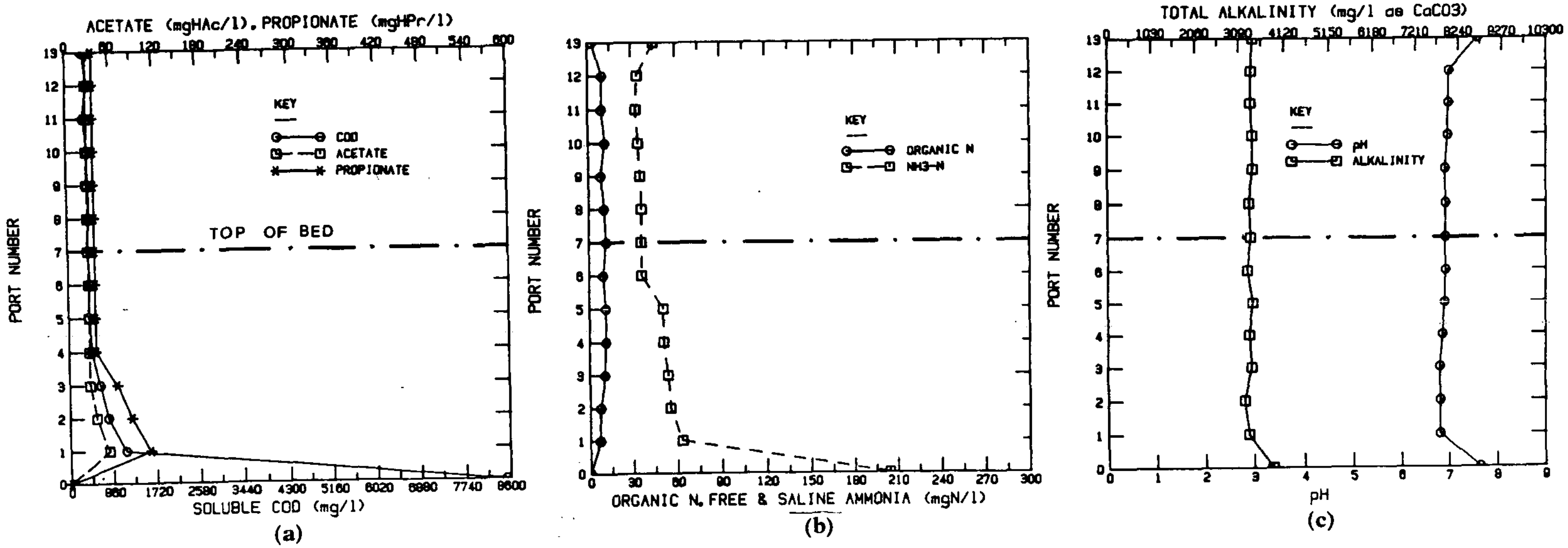
Figure 5
Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 5 700 mg/ℓ; flow rate = 15 ℓ/d; recycle ratio = 2:1; Table 1, Exp. B3)



(a) (b) (c)

Figure 6

Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 8 500 mg/ℓ; flow rate = 15 ℓ/d; recycle ratio = 0:1; Table 1, Exp. C1)



(a) (b) (c)

Figure 7

Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 8 500 mg/ℓ; flow rate = 15 ℓ/d; recycle ratio = 2:1, Table 1, Exp. C3)

$$\text{Effective Akl/COD} = \frac{(\text{base + recycle flows})\text{x}(\text{Base Alk/COD})}{(\text{base flow})}$$

- With a recycle, provided the effective Alk/COD ratio was maintained at ≥ 1,2 mg alkalinity (as $CaCO_3$)/mg influent COD, the system response remained relatively stable and the pH ≥ 6,6; there was even a slight improvement in system performance.

It is not possible to assign a substantive reason for the slight improvement in COD removal after introduction of a recycle. Very likely the fine volatile suspended solids present in the recycle stream may have contributed to improving the system performance; pellet debris accumulated in the region above the sludge bed as a suspended blanket with a volatile suspended solids (VSS) concentration between 6 and 13 gVSS/ℓ, depending on the loading rate. The suspended material exhibited no biological activity (there was no significant difference between the COD in the suspended blanket zone and the upper zone of the pelletised bed; see Figs. 1 to 5). However, tests on the suspended material indicated that when this was fed with glucose at a COD concentration above 2 000 mg/ℓ, biological activity took place and COD was removed from solution. Hence, in the recycle experiments the debris material recycled into the feed line could have assisted in the COD reduction. There was ample contact opportunity between the debris material and the influent because the recycle and base flows were blended at a junction nearly 1 m upstream of the entry point to the reactor.

The apparent "inert" behaviour of the suspended blanket above the bed is an interesting one. It might point to some deficiency of a nutrient developing up the bed. Sam-Soon *et al.* (1990b) have indicated that the nitrogen requirement for acidogenic growth is greater in UASB than in completely mixed anaerobic systems. In completely mixed systems the nitrogen requirements are reduced due to nitrogen feedback from death processes; in the UASB system nitrogen feedback is limited due to the plug flow mixing regime. In a similar fasion it is feasible that increased concentrations of other essential nutrients also may be required. Up to the present, for example, the sufficiency of phosphate has been accepted, based on the adequacy of its concentration as normally supplied in completely mixed systems.

Recycles at maximum loading

To investigate the effect of recycle at or near the maximum loading rate on the system (estimated by Sam-Soon *et al.*, 1987, at ± 44 kgCOD/m^3 sludge bed volume.d) the influent COD concentration was set at about 8 500 mgCOD/ℓ, flow rate at 15 ℓ/d (loading 42,5 kgCOD/m^3 sludge bed volume.d), alkalinity in the feed at Alk/COD of 1,22 and no recycle (Exp. C1, Table 1). The system operated in a stable fashion, minimum pH 6,7 but the performance was slightly lower at 91 per cent overall COD removal. Concentration profiles for the system are shown in Fig. 6 (a),(b) and (c). Imposing a 1:1 recycle (Exp. C2, Table 1) and decreasing the alkalinity to 0,71 (effective Alk/COD ratio of 1,42 mg alkalinity (as $CaCO_3$)/mg influent COD), the minimum pH increased to 6,8 and overall COD removal improved to 96 per cent. Increasing the recycle ratio to 2:1 (Exp. C3, Table 1) and decreasing the alkalinity supplementation in the feed to 0,45 (i.e. effective Alk/COD ratio was 1,35 with a 2:1 recycle), the minimum pH and overall COD removal remained constant, at 6,8 and 96 per cent respectively. Concentration profiles for the system with a 2:1 recycle are shown in Fig. 7(a), (b) and (c). Increasing the recycle ratio to 3:1 (Exp. C4, Table 1) but keeping the alkalinity supplementation of 0,46 (i.e. effective Alk/COD ratio is 1,84), the minimum pH remained unchanged (i.e. pH 6,8) but the overall COD removal declined slightly to 92 per cent; concentration profiles for this system are shown in Fig. 8 (a),(b) and (c).

Although a reduction in COD removal from 96 to 92 per cent can hardly be thought of as indicating a tendency to failure, it does sound a warning as to potential adverse effects of the recycle in a system which is operating at or near its maximum loading rate. In Table 2 the influent and effluent COD and SCFA are listed against the set of recycle ratios. These give little indication of possible causes of stress induced by the recycle ratios. In Table 3 the daily masses of COD and SCFA in the influent, effluent and recycle flows are listed against the recycle ratios. It is now apparent that the masses of COD and SCFA recycled to the influent line increased as the recycle ratio increased and that the effective loading rate on the sludge bed correspondingly increased. For example, at the recycle ratio of 3:1 the COD mass recycled was 24 per cent of the base loading rate. Even though a fraction of the recycled COD may be inert, a substantial increase in the loading rate, to over 50 kg/m^3 sludge bed volume.d, was being imposed. Thus, for a system at or near its maximum sludge bed loading rate, with a relatively high recycle ratio, any perturbation that increases the effluent COD and/or SCFA would cause a disproportionate increase in the effective loading rate on the sludge and could interactively give rise to a progressive decline in the performance, eventually leading to failure.

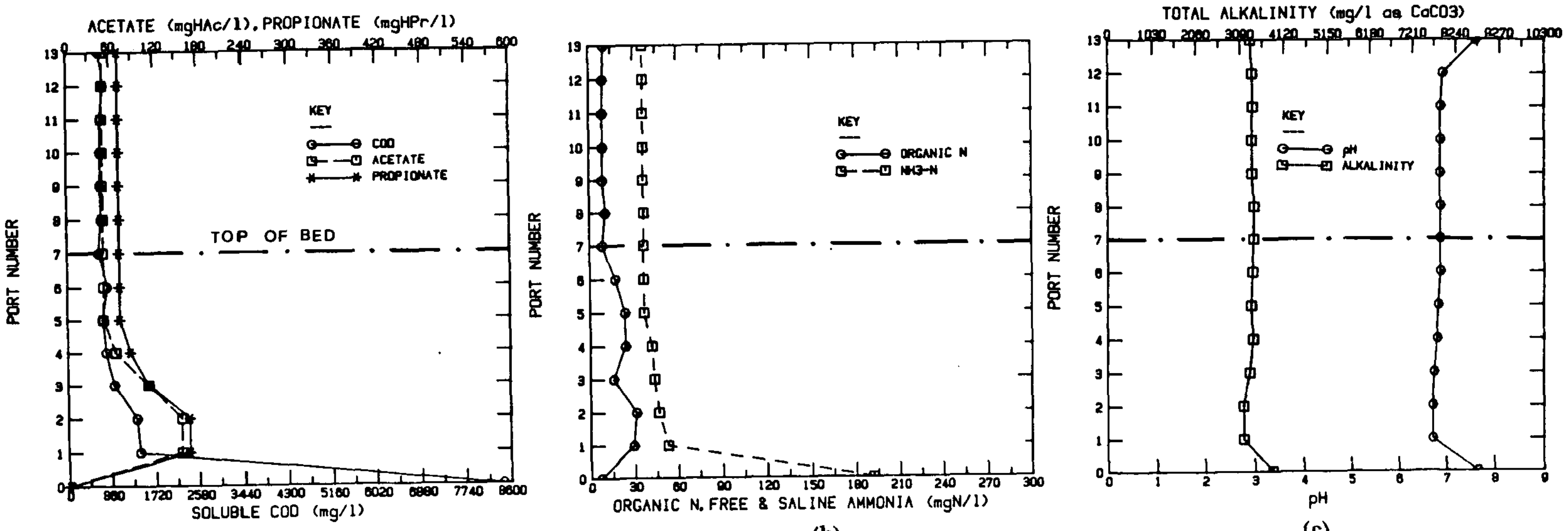
At loading rates substantially less than the maximum, self-induced failure due to the presence of a recycle is not likely. This statement is supported by the data presented earlier in the paper in which higher recycles in fact improved the system performance. Furthermore, in studies on a UASB system treating spent wine waste waters with an influent COD ≈ 20 00 mg/ℓ, a loading rate of 20 kgCOD/m^3 sludge bed volume.d (substantially less than the maximum rate) and recycle ratios as high as 15:1, the performance of the system remained stable with regard to COD removal and pellet formation (data not shown). Incorporation of recycles to reduce alkalinity supplementation therefore can be implemented with no apparent risk, provided the loading rate is substantially less than the maximum.

Maximum loading rates

Determination of the maximum loading rate on a UASB system is not yet adequately resolved. The difficulty is that the causes of failure in a UASB system are not yet understood. Accordingly we are forced to define failure empirically, for example, by accepting a state of failure when the effluent propionate and soluble COD commence to show undue increase; such a definition is in terms of symptoms, not in terms of causes.

In terms of the above definition of failure, Sam-Soon (1990) identified the following factors that influence the maximum loading rates in UASB systems treating carbohydrate wastes, provided the minimum pH in the bed is ≥ 6,6 and adequate nutrients and excess nitrogen were available in the influent.

- ***Increment of loading rate increase:*** The maximum loading rate appears to be higher if the maximum rate is approached by using smaller increments of load increase. At daily increments of 0,6 kgCOD/m^3 sludge bed volume.d the maximum loading rate was about 44 kgCOD/m^3 sludge bed volume.d. At daily increments of 0,38 kgCOD/m^3 sludge bed volume.d the maximum loading rate was 70 kgCOD/m^3 sludge bed volume.d. Insufficient work has been done to determine whether the higher maximum rate is "stable" or whether the lower maximum rate



(a) (b) (c)

Figure 8

Concentration and pH profiles observed in UASB system with apple juice concentrate as substrate (Influent COD = 8 500 mg/ℓ; flow rate = 15 ℓ/d; recycle ratio = 3:1; Table 1, Exp. C4)

TABLE 2

EFFECT OF THE RECYCLE RATIO ON EFFLUENT QUALITY IN A UASB SYSTEM AT NEAR MAXIMUM LOADING RATE (APPLE JUICING WASTE, TEMPERATURE 30°C, LOADING RATE 42,5 kgCOD/m^3 SLUDGE BED VOLUME.d)

Influent COD* mg/ℓ	Recycle ratio recycle: base flow	Effluent and recycle COD mg/ℓ	SCFA mg/ℓ* HPr	HAc	COD reduction %
8 500	0:1	687	61	100	90,6
8 500	1:1	340	-	-	96,0
8 500	2:1	397	37	28	95,3
8 500	3:1	678	72	50	91,9

*To convert mgHPr and mgHAc to mgCOD multiply by 1,512 and 1,067 respectively

TABLE 3
EFFECT OF RECYCLE ON EFFECTIVE SLUDGE BED MASS LOADING RATE IN A UASB SYSTEM AT NEAR MAXIMUM LOADING RATE (APPLE JUICING WASTE, TEMPERATURE 30°C, LOADING RATE 42,5 kgCOD/m³ SLUDGE BED VOLUME.d).

Influent COD g/d	Recycle ratio recycle:base flow	COD g/d Effluent	COD g/d Recycle	SCFA gCOD/d Effluent	SCFA gCOD/d Recycle	% increase in COD load
126,0	0:1	11,97	0	2,96	0	0
127,5	1:1	5,10	5,1	-	-	4,0
127,5	2:1	5,96	11,9	1,29	2,6	9,3
126,6	3:1	10,17	30,5	2,43	7,3	24,1

would have increased in time if the system had been operated at below maximum for a time sufficient for the organism mass to achieve greater adaption.

- ***Temperature:*** The maximum loading rate is very sensitive to temperature. Dold *et al.* (1987) showed that for two UASB systems treating apple juicing wastes, at 25°C and 30°C respectively, with same increments in loading rate increase (0,6 kgCOD/m³ sludge bed volume.d) and influent COD 2 500 mg/ℓ, the maximum loading rates were about 29 and 44 kgCOD/m³ sludge bed volume.d repectively, i.e. a decline of 34 per cent for a 5°C decline in temperature. It may be fortuitous but of interest to note that according to Henze and Harremöes (1983) the relationship between the overall rate of mesophyllic anaerobic processes and temperature in the range 10 to 30°C is:

$$\frac{\text{Rate } T^1}{\text{Rate } T^2} = e^{0,1(T1-T2)}$$

For the temperatures T1 = 25°C and T2 = 30°C:

$$\text{Rate } 25°\text{C} = 0,61 \text{ Rate } 30°\text{C}$$

In the maximum loading rate study reported here:
Maximum loading rate 25°C = 0,66 maximum loading rate 30°C.

- ***Influent COD concentration:*** Sam-Soon (1990) concluded that for influent COD concentrations in the range 2 000 to 5 000 mgCOD/ℓ, in flow-through systems, for the same increment of loading rate increase, the maximum loading appears to be independent of the influent COD concentration.

The effects of the factors above suggest the following experimental guidelines for determining a "standardised" maximum loading rate in a UASB system treating a carbohydrate waste:

- Ensure that adequate nutrients and excess nitrogen and alkalinity are available in the influent (mgNH_3-N/mg influent COD > 0,017 to 0,02; mg alkalinity (as $CaCO_3$)/mg influent COD > 1,2 to 1,6).
- With strong wastes dilute the waste water into the range 2 000 to 5 000 mg/ℓ.
- Set up a flow-through UASB system.
- Select the operating temperature, for example, 30°C, and control the system to this temperature within 1/2°C.
- Inaugurate the system following the procedure suggested by Dold *et al.* (1987).
- Once pellet formation has been established, apply a daily increment in loading rate increase of > 0,5 kgCOD/m³ sludge bed volume.d.
- Monitor the SCFA, COD, alkalinity, pH, NH_3-N, TKN of effluent and, measure bed profiles of these; ensure that the minimum pH in the bed is 6,6 < pH < 7,0 by controlling alkalinity in the influent. The maximum loading rate is identified by a decline in COD removal and increases in the effluent SCFA.

Having determined the maximum loading rate, the operating loading rate should be selected at a much lower value, say 1/4 to 1/2 of the maximum, to accommodate factors likely to be encountered at full scale, e.g. fluctuations in temperature and loading rate, variable influent composition (in COD, SCFA, alkalinity, pH and nutrients) and shock loadings. Prior to full-scale implementation, the response of the UASB system to the waste water at the operating loading rate should be tested at laboratory and pilot scale to assess whether deficiencies in trace and major nutrients are present, shown by the development of gelatinous or filamentous sludges, reduced pellet formation or other deviant behaviour. Guidelines for process design will be given in a later paper.

Conclusions

In this paper an assessment has been made of the effects of a recycle on the performance of a UASB system, in particular on the alkalinity requirements. The following conclusions are derived from this study:

- For a flow-through UASB system treating a virtually pure carbohydrate substrate, apple juice waste water, the minimum alkalinity requirement per influent COD is found to be > 1,2 mg alkalinity (as $CaCO_3$)/mg influent COD in order to maintain the minimum pH ≥ 6,6 in the sludge bed.
- The alkalinity requirement per influent COD can be reduced by imposing a recycle; the reduced requirement can be calculated by multiplying the basic alkalinity requirement per influent COD (1,2 mg alkalinity/mg influent COD) by the factor [flow/(flow + recycle flow)].
- Provided the loading rate (kgCOD/m³ sludge bed volume.d) is substantially less than the maximum loading rate (say 1/4 to 1/2 of the minimum loading rate) imposing a recycle (to reduce the effective influent COD concentration or the alkalinity requirement per influent COD) does not affect the system performance adversely. Recycle ratios of up to 15:1 have operated

completely satisfactorily.

- When the loading rate on a flow-through system approaches the maximum, increasing concentrations of COD and SCFA appear in the effluent. Recycling the higher COD and SCFA concentrations has an adverse effect on the performance of the system, and conceivably can cause failure, by inducing a higher effective COD loading rate on the sludge mass.
- The effective influent COD concentration of a waste should be in the range 1 000 to 5 000 mgCOD/ℓ. For strong wastes the effective influent COD can be brought into this range by imposing an appropriate recycle from the effluent to the influent; the alkalinity requirements per influent COD will be reduced accordingly.

Acknowledgements

This research was supported jointly by the Foundation for Research Development and the Water Research Commission of South Africa and this paper is published with their permission.

References

CAPRI, MG (1973) Anaerobic filter treatment of wine distillery waste. M.Sc. Thesis, Dept. Civ. Eng., Univ. of Cape Town, Rondebosch 7700, South Africa.

CRONJE, CPR (1973) Treatment of a glucose-starch waste by anaerobic filter process. M.Sc. Thesis, Dept. Civ. Eng., Univ. of Cape Town, Rondebosch 7700, South Africa.

DOLD, PL, SAM-SOON, PALNS, PALMER, IH and MARIAS, GvR (1987) Anaerobic treatment of an apple processing wastewater. *Wat.Sci.Tech.* **19** 237-247.

HENZE, M and HARREMOËS, P (1983) Anaerobic treatment of wastewaters in fixed film reactors: Review paper. *Wat.Sci.Tech.* **15** 1-101.

LOEWENTHAL, RE, EKAMA, GA and MARAIS, GvR (1989) Mixed weak acid/base systems. Part I: Mixture characterisation. *Water SA* **15**(1) 3-24.

SAM-SOON, PALNS (1990) Pelletization in the upflow anaerobic sludge bed (UASB) reactor. Ph.D. Thesis, Dept. Civ. Eng., Univ. of Cape Town, Rondebosch, 7700, South Africa.

SAM-SOON, PALNS, LOEWENTHAL, RE, DOLD, PL and MARAIS, GvR (1987) Hypothesis for pelletisation in the upflow anaerobic sludge bed reactor. *Water SA* **13**(2) 69-80.

SAM-SOON, PALNS, LOEWENTHAL, RE, WENTZEL, MC and MARAIS, GvR (1990a) Growth of biopellets on glucose in upflow anaerobic sludge bed (UASB) systems. *Water SA* **16**(3) 151-164.

SAM-SOON, PALNS, LOEWENTHAL, RE, WENTZEL, MC and MARAIS, GvR (1990b) Effect of nitrogen limitation on pelletisation in upflow anaerobic sludge bed (UASB) systems. *Water SA* **16**(3) 165-170.

STANDARD METHODS (1985) *Standard Methods for the Examination of Water and Wastewater* (16th edn.). American Public Health Association, Washington DC, USA.

YOUNG, JC and McCARTY, PL (1967) Operational characteristics of anaerobic packed-bed reactors. *Biotechnology and Bioengineering Symp.* **12** 303-316.