Experiments and modelling on biomass transport inside upflow sludge blanket reactors intermittently fed

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Abstract

This paper describes the experimental and theoretical activities developed to study the biomass transport phenomena occurring in upflow anaerobic reactors influencing the biomass washout. Particularly, the experimental investigations have been carried out on a full-scale ABR and on a pilot UASB intermittently fed with the aim to determine the extent to which washout is affected by: daily flow distribution; upflow velocity; concentration and sedimentation properties of the biomass. The theoretical study focused on the proposal of a mathematical model able to simulate the sludge transport phenomena in the above cited reactors, in order to obtain a tool to estimate sludge washout in different influent flow conditions.

The research has shown the considerable influence on the biomass behaviour of the time interval occurring between two successive feeds of the reactors. In fact, if this period is more than 1 h considerable losses of biomass into the effluent were found, independent of the upflow velocity. On the other hand, shorter periods give rise to a regular sludge expansion of the interface even with very high upflow velocities (up to 4 m·h^{-1}), and consequently to limited sludge washout.

Keywords: UASB, sludge washout, solids transport model

Introduction

The anaerobic biological sludge blanket systems proposed over recent years have elicited considerable interest because of their good removal efficiencies of organic substrates, their relatively simple layout and the low capital and operating costs. The most successful systems include the upflow anaerobic sludge blanket (UASB - Lettinga et al., 1980) and the anaerobic baffled reactor (ABR – Bachmann et al., 1985; Barber and Stuckey, 1999). UASBs are comprised of a tank fed from below in which the wastewater to be treated flows vertically upwards: the biomass forms a thick layer of sludge on the bottom beneath a suspension composed of biologically formed granules (blanket). ABRs consist of two or more tanks (sections) arranged in series, each of which acts like a UASB, so that the acid-forming bacteria are separated from the methane-forming ones and the methane fermentation process is not affected by an over-production of organic acids (Barber and Stuckey, 1999).

The granule washout into the final effluent of UASBs and ABRs is obviously a critical feature in the operation of these systems. If this were to happen, system performance would drop as a result of the presence of organic solids in the effluent (Grobicky and Stuckey, 1991; 1992; Lettinga and Hulshoff Pol, 1991) and the reduction of the biomass in the system (Nachaiyasit and Stuckey, 1997). However, continuously fed systems have shown fairly small washout even with high average upflow velocities, in the order of 1to 1.5 m·h^{-1} (Barber and Stuckey, 1999; Orozco, 1997), a result which is essentially attributable to the good sedimentation properties of anaerobic sludges. There is no information available on the washout in systems intermittently fed, which is essential in the wastewater treatment plants of small communities (Garuti et al., 1992; Garuti et al., 2001).

This paper describes the problem of washout in intermittently fed anaerobic systems by referring to experimental tests carried out in a variety of working conditions. These were made possible by using the full-scale ABR and the pilot UASB respectively located at the Biancolina (Bologna, Italy) Wastewater Treatment Plant (WWTP) and at the laboratory of the National Agency for New Technologies, Energy and Environment (ENEA). The tests aimed to determine the extent to which treatment performance is affected by factors such as: daily flow distribution; upflow velocity; concentration and sedimentation properties of biomass. In order to generalise the obtained results, a simulation model of the sludge transport phenomena in the two biological systems is proposed.

The work was organised in three phases. Phase 1 analysed the washout phenomenon in the two anaerobic sections of the ABR at Biancolina WWTP by monitoring the sludge concentration under different flow conditions.

Phase 2 of the research was carried out in the laboratory using a plexiglass pilot UASB inoculated with the sludge from the first section of the ABR located at the Biancolina WWTP and fed with a flow having the same organic matter concentration so as to reproduce operating conditions close to those of the actual system and also physically observe sludge dynamics in the system. Repeated measurements of the total suspended solids (TSS) and soluble COD content of the effluent made it possible to determine washout entity and removal efficiencies according to the way the blanket expands.

Finally, Phase 3 deals with the implementation of a mathematical model that can simulate biomass transport in a UASB (or in each section of an ABR) in order to estimate washout under different influent flow conditions.

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TABLE 1
Operating conditions for tests on the ABR of the Biancolina WWTP

Test	Data	D_f (min)	D_i (min)	D_c (min)	u ($m \cdot h^{-1}$)	D_s (min)
1	2	3	4	5	6	7
1	03/11	5	12	17	2.30	100
2	04/11	10	15	25	2.30	10
3	11/11	18	60	78	2.30	28
4	17/11	22	120	142	2.30	40
5	14/12	18	60	78	1.40	28

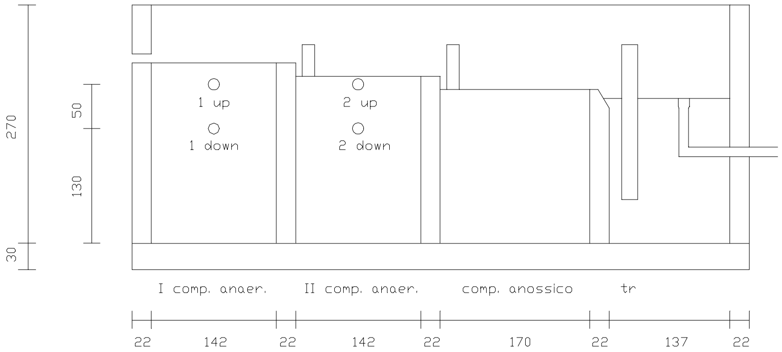

Figure 1
Schematic representation of the ABR located at the Biancolina WWTP

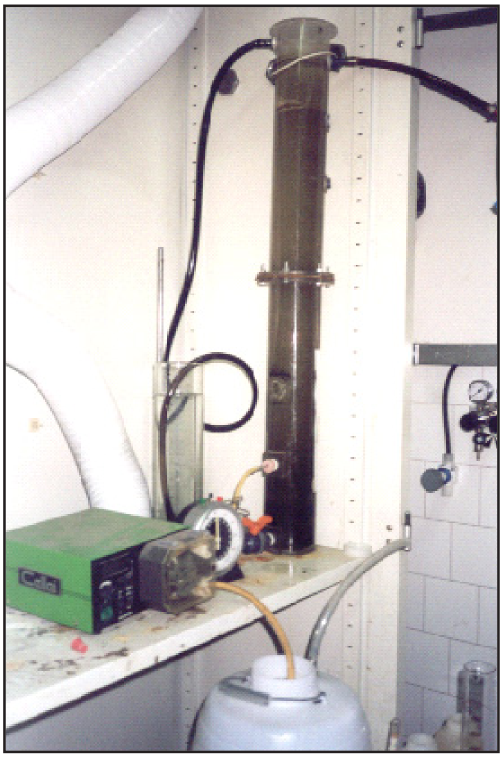

Figure 2
UASB pilot plant

Materials and methods

Phase 1 of the experimental activities was carried out at the Biancolina WWTP which comprises (Garuti et al., 2001): an ABR with three sections for an overall volume of 24.2 m^3, and a sludge trap (Fig. 1); an activated sludge biological system with an aeration tank and a settling tank; and a thickening tank for excess sludge. In the first two sections of the ABR (with respective volumes of 8.2 and 7.6 m^3 and each with a surface area of 4.0 m^2) the organic substrate content of influent wastewater is partially degraded by biomass in anaerobic conditions; in the third section (surface area and volume are 4.8 m^2 and 8.4 m^3, respectively) the nitrates produced in the aerobic tank are transformed to molecular nitrogen by recycling part of the effluent from the final settling phase. The incoming wastewater is pumped up by two alternate-operation open-impeller electro-pumps, controlled by a timer system or by ball-cocks. Designed to serve 350 equivalent inhabitants with a mean wastewater flow of about 40 $m^3 \cdot d^{-1}$, during the trial period (September to December, 1999) the plant was fed with a mean flow of just 18.3 $m^3 \cdot d^{-1}$.

In order to assess the extent to which the various conditions of intermittent feed affect washout, five tests were carried out (Table 1, Columns 1 and 2). These differed in: the duration of the feed phases (D_f, Column 3); the duration of the feed interruption phases (D_i, Column 4); the duration of the cycle (D_c, Column 5), which is given by the sum of the above two times; and the upflow velocity of the flow being treated (u, Column 6). In particular, during Tests 1, 2, 3 and 4 the hourly volume of wastewater fed to the plant was maintained at a constant rate of 9.20 $m^3 \cdot h^{-1}$, while for Test 5 it was 5.56 $m^3 \cdot h^{-1}$. Tests 3, 4 and 5, characterised by a longer duration of the feed phases, were carried out by recycling the excess water from the thickening tank through the pumping shaft.

For all the tests, sludge was sampled from the two anaerobic sections of the ABR during the intervals (D_s) summarised in Column 7 of Table 1. This was achieved using samplers located at 1.30 m and 1.80 m from the bottom (Fig. 1) and called "**1 up**", "**1 down**", "**2 up**" and "**2 down**". Sampling always began at the same time as the start of a feed phase although it normally lasted longer. The TSS concentration was measured for all sludge samples in compliance with the *Standard Methods* (1989). The first two tests entailed a small number of measurements and were needed above all to calibrate the experimental activity. Consequently the following comments will refer mainly to the remaining three tests.

The sludge from the first section of the ABR was also subjected to six sedimentation tests in order to obtain the expression correlating settling velocity to TSS concentration, useful to the mathematical model described below. The measurements were taken according to *Standard Methods* (1989) and using sludge samples with a TSS concentration between 3 500 and 6 800 $g \cdot m^{-3}$.

Phase 2 of the experiments was carried out using a pilot plant made of a plexiglass cylinder with an internal diameter of 0.10 m and a height of 1.20 m (Fig. 2). Before commencing the tests, the plant was filled up to a height of 1.05 m with $0.94 \cdot 10^{-3} \cdot m^3$ of sludge and $7.30 \cdot 10^{-3} \cdot m^3$ of wastewater from the first section of the ABR at Biancolina WWTP. During the tests it was fed predominantly with a mixture of tap water and glucose having a total COD of 230 $g \cdot m^{-3}$ (equal to the mean value measured in the influent flow at the Biancolina WWTP). In order to check the experimental results, some tests were repeated using wastewater from the Biancolina WWTP and these gave acceptable results. In all cases the temperature and pH of the flow fed to the pilot plant were maintained at almost constant values of 17° C and 6.9, respectively.

Experimentation consisted of 10 different tests (Table 2,

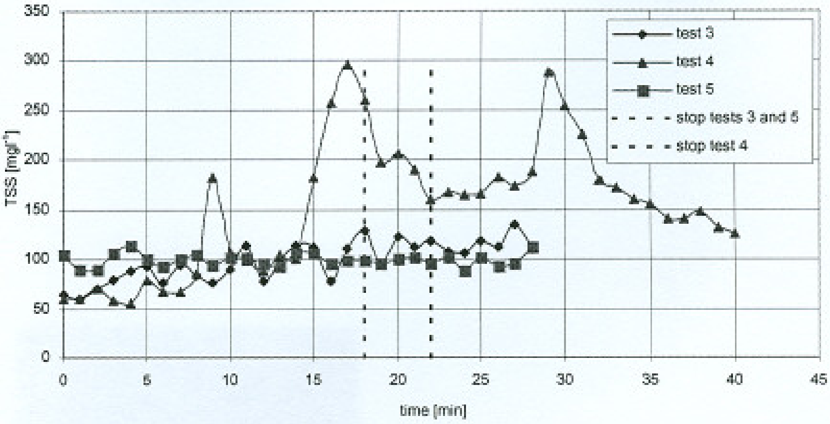

Figure 3
Trend of TSS concentration in the sludge extracted by the 1 up sampler of the Biancolina ABR

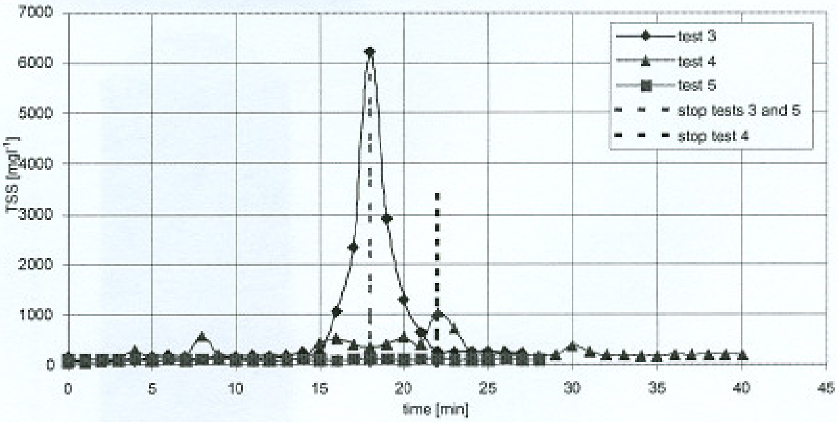

Figure 4
Trend of TSS concentration in the sludge extracted by the 1 down sampler of the Biancolina ABR

Column 1), characterised by different values of D_c (Column 2) or, more specifically, by different values of D_f and D_i (Columns 3 and 4). For each test, plant operation was examined with different values of u (Column 5), for each of which were carried out several repeatedly investigations (Column 6). In all cases the way in which the sludge blanket expanded was observed and analysed and the height it reached inside the pilot plant was measured.

All the investigations in Test 1 lasted 80 min, which is four times D_c. During this time interval, the TSS and soluble COD concentrations in the effluent were measured at the peaks of sludge blanket expansion (after about 10, 30, 50 and 70 min from test start).

Phase 3 of the work was concerned with the setting up of a mathematical model for the simulation of washout in the UASBs. The model was calibrated according to the results obtained during the experimental tests and was used to establish a correlation between washout and the various factors affecting it.

Analysis and comments

Tests carried out on the ABR at the Biancolina WWTP

Figures 3 and 4 report the trend of TSS concentrations detected in the first section of the ABR at the Biancolina WWTP during Tests 3, 4 and 5; the origin of the abscissa axes corresponds to the start of flow feed; the dashed vertical segments indicate the times at which the feed was interrupted. In particular, Fig. 3 shows diagrams of the TSS concentrations in the sludge taken by the **"1 up"** sampler while Fig. 4 reports the relative values for the **"1 down"** sampler.

An examination of the figures shows, first of all, that the TSS concentrations were always (even at the very beginning of the tests) at least 60 to 80 g·m^{-3} (on average 70 g·m^{-3}) because of the presence of colloids evenly distributed in the ABR. These colloids presumably derive from the partial fragmentation of the granules caused by local turbulence, above all when a new feed is delivered. These can be said to represent the minimum washout of the ABR, to which may be added other particles transported by the wastewater flow to be treated.

The tests have shown that sludge washout in the ABR is affected to a differing extent by the upflow velocity and the plant feed conditions. In particular, with u equal to 2.30 m·h^{-1} and small D_c values (Tests 1 and 2), the TSS concentrations were low both in the sludge taken by the **"1 down"** sampler and, more obviously, in that extracted by the **"1 up"** sampler. For the same values of u, and increasing D_c (Test 3), a considerable increase in the TSS concentrations of the sludge extracted by the **"1 down"** sampler was seen after the 15th minute from feed phase start. This result has been attributed to the sudden rising in the sludge bed inside the reactor, whose effects are not however affected by the height of the **"1 up"** sampler (Fig. 3).

Making further increases to D_c (and, in particular, taking D_i to 2 h) showed (Test 4) a decrease in the TSS concentrations of the sludge extracted by the **"1 down"** sampler and a corresponding increase in the values measured in the area of the **"1 up"** sampler, with a consequential greater uniformity of the TSS concentrations along the first section of the ABR. This trend was justified by hypothesising a veritable explosion in the sludge blanket, which this time reached the height of the **"1 up"** sampler.

The entity of the sudden rising of the sludge blanket obviously also depends on the upflow velocity. The rise measured during Test 5 was, in fact, lower than that of Test 3, which had the same D_c but a higher u.

The settling velocity values (V_S, in m·h^{-1}) of the sludge in the first section of the ABR detected during the six sedimentation tests mentioned in the previous paragraph are reported in Fig. 5 as a

TABLE 2
Operating conditions and results of tests on the UASB pilot plant

Test	D_c (min)	D_f (min)	D_i (min)	u (m•h^{-1})	Number of investigations	Investigations with blanket regular expansion	Investigations with blanket regular expansion (%)
1	2	3	4	5	6	7	8
1	20	10	10	2.15	20	20	100
	20	10	10	2.34	20	20	100
	20	10	10	2.58	20	20	100
	20	10	10	3.06	20	20	100
	20	10	10	3.44	20	20	100
	20	10	10	3.70	20	19	95
	20	10	10	4.17	20	19	95
	20	10	10	4.59	20	18	90
	20	10	10	4.91	20	18	90
2	30	10	20	2.15	10	10	100
	30	10	20	2.34	10	10	100
	30	10	20	3.70	10	10	100
	30	10	20	4.91	10	9	90
3	40	10	30	2.34	10	10	100
	40	10	30	3.70	10	10	100
	40	10	30	4.91	10	10	100
4	50	10	40	2.34	10	10	100
	50	10	40	3.70	10	9	90
	50	10	40	4.17	10	9	90
	50	10	40	4.91	10	9	90
5	70	10	60	2.15	10	9	90
	70	10	60	2.34	10	10	100
	70	10	60	3.44	10	9	90
	70	10	60	3.70	10	9	90
	70	10	60	4.91	10	8	80
6	100	10	90	2.34	10	7	70
	100	10	90	3.70	10	4	40
	100	10	90	4.17	10	2	20
	100	10	90	4.91	10	0	0
7	190	10	180	2.34	6	3	50
	190	10	180	3.70	6	1	17
	185	5	180	4.17	6	0	0
	185	5	180	4.91	6	0	0
8	490	10	480	2.34	3	0	0
	485	5	480	3.70	3	0	0
	485	5	480	4.17	3	0	0
	485	5	480	4.91	3	0	0
9	1505	5	1500	2.15	3	0	0
	1505	5	1500	2.34	3	0	0
	1505	5	1500	3.70	3	0	0
10	3605	5	3600	2.15	3	0	0
	3605	5	3600	2.34	3	0	0
	3605	5	3600	3.70	3	0	0

function of the sludge's TSS concentration (C, in kg·m^{-3}). The correlation between V_S and C is well interpolated by the following power relationship ($R^2 = 0.963$):

$$V_S = 15.005 \cdot C^{-0.88} \qquad (1)$$

Tests carried out on the UASB pilot plant

In order to verify the results of what ultimately was a small number of experiments carried out on the Biancolina ABR, a much larger number of further tests was conducted using the plexiglass pilot UASB set up in the laboratory and varying D_i and u. The main advantage of this second series of experiments consists in observing the expansion of the sludge blanket.

Ten tests were carried out with different values of D_i: for the first five tests it was less than or equal to 1 h; for the others it was > 1 h. The results of the first five tests (Table 2, Columns 7 and 8) show that the sludge blanket almost always expanded regularly, regardless of the upflow velocity (some discrepancies were observed only for u close to 4 m·h^{-1} or higher). Under these conditions, a clear interface in the sludge blanket was seen to form and, at the moment of maximum expansion, fairly small TSS concentrations were always measured (Fig. 6, for Test 1).

Increases in D_i (Tests 6 to 10) showed a significantly thickened sludge blanket on the bottom during the feed interruption phases; the formation of numerous channels in the sludge blanket when the feed started; most of the wastewater flow passing at high speed (much higher than u) through these channels during the feed phases, with a consequent 'short circuiting' of the sludge blanket, the formation of an irregular interface (which actually disappeared for D_i greater than 3 h) and high TSS concentrations in the effluent. Moreover, increases in D_i led to a greater volume of biogas trapped in the sludge blanket, which was obviously released (in the form of large bubbles) at the start of feeding and further contributed to the irregular expansion of the sludge blanket in the form of some kind of explosion.

The influence of upflow velocity on sludge blanket expansion was assessed on the basis of the considerations made above, by referring to regular expansion conditions. In particular, the results of Test 1 were used. These were obtained with D_i equal to 10 min and relative to nine different values of u; the trend over time of the height of the sludge blanket interface during four successive cycles is reported in Fig. 7. As can be seen, periodic steady-state conditions were reached in all cases after just two cycles. Obviously the interface reached gradually higher levels as u increased. The height increase was particularly significant when the upflow velocity passed from 2.58 $m \cdot h^{-1}$ to 3.06 $m \cdot h^{-1}$. All the curves show a rapid rise in the sludge at an almost constant speed immediately following the start of feeding and as it continues, the curves show a concave trend indicating a fall in the interface rising speed after the gradual dispersion of the granules which were less subject to wastewater flow transport effects.

The influence of upflow velocity on washout was established by means of the above-mentioned measurements of suspended solids in the plant effluent (Fig. 6). As these measurements are held to be coincident with the mean value of the TSS concentration in the effluent during a 5 min interval around the moment of maximum sludge blanket expansion, it was possible to calculate the sludge mass escaping into the effluent during this interval. This value was held to be a significant index of the measurement of overall system washout (M_W, Column 2, Table 3) as it constituted a certainly high percentage of the washout and was generally increasing as u increased. Column 3 of Table 3 reports the values indicated with m_W and obtained by the ratio of M_W with the sludge mass present in the plant at the beginning of the test. The value of m_W was seen to range between 0.17 and 0.25 % so long as u was not higher than 4.17 $m \cdot h^{-1}$. Moreover, in these conditions the correlation between upflow velocity and washout was, with sufficient approximation, linear (Fig. 8). With values of u higher than 4.17 $m \cdot h^{-1}$, m_W exceeded 0.3 %, even with regular sludge blanket expansion. This trend was probably caused by local turbulence which, on the one hand favours granule fragmentation and, on the other, increases their detachment at the sludge blanket interface.

During each investigation in Test 1 the COD of effluent flowing out of the pilot plant was determined after being filtered to eliminate the washout contribution. The mean values corresponding to each upflow velocity and the relative removal efficiencies are reported in Table 3 (Columns 4 and 5

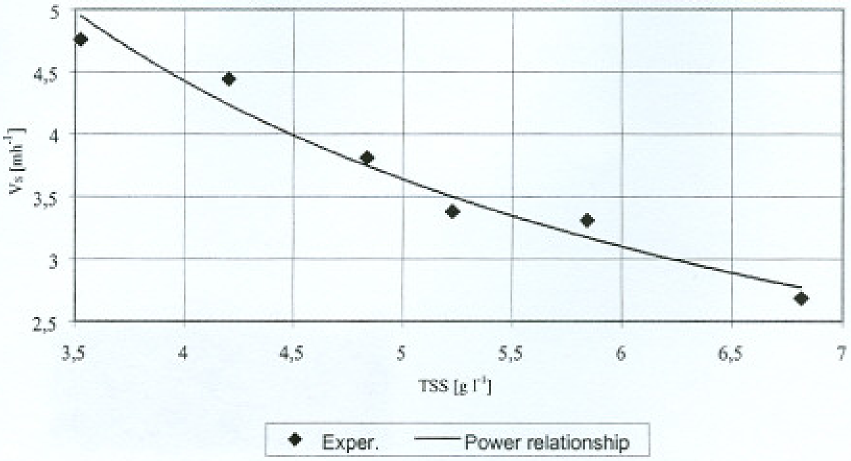

Figure 5
Sedimentation velocity of the sludge of the Biancolina ABR as a function of TSS concentration

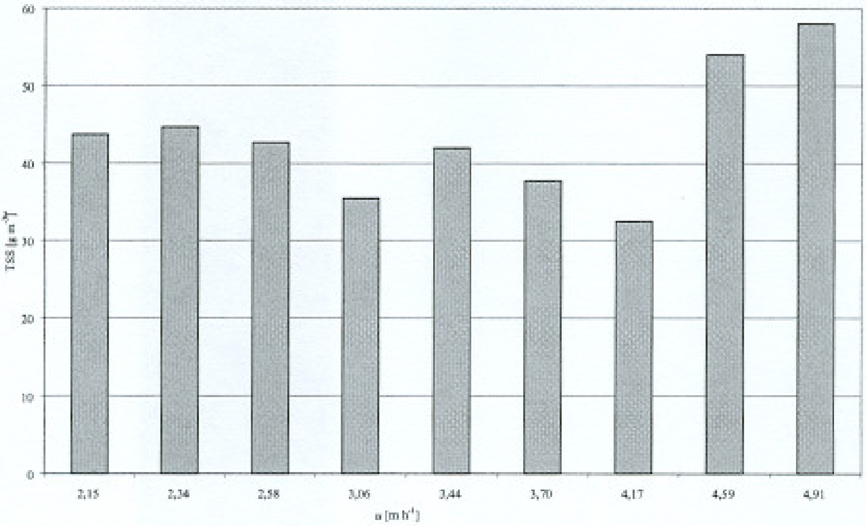

Figure 6
Mean TSS concentrations detected in the effluent of the pilot UASB during Test 1 at the moment of maximum sludge blanket height

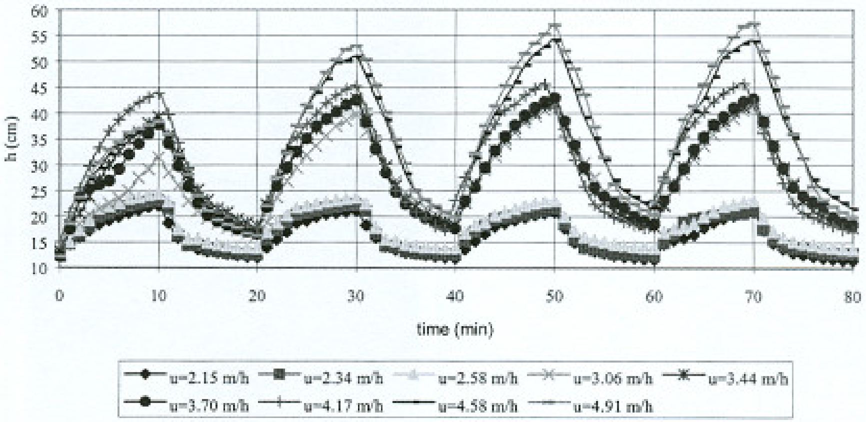

Figure 7
Trend of the sludge blanket interface height detected in the pilot UASB during Test 1

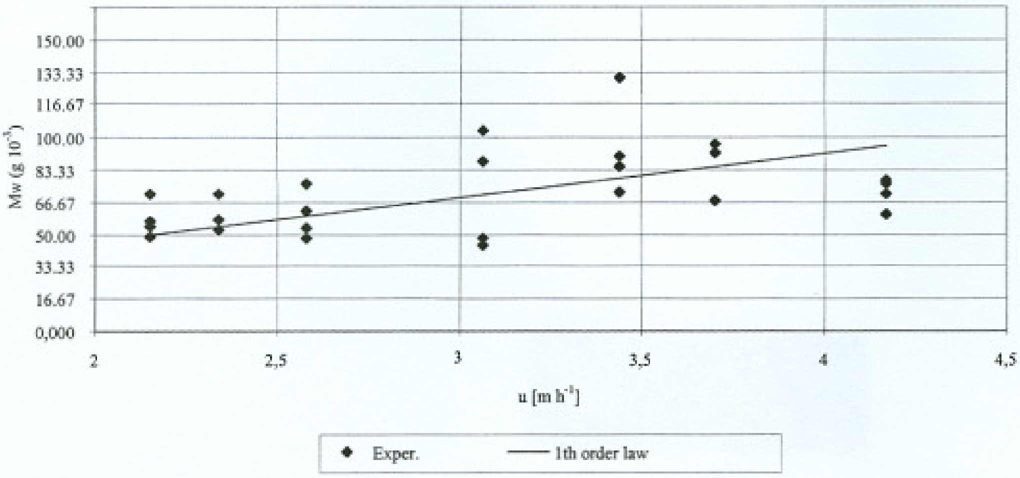

Figure 8
Correlation between washout and upflow velocity ($R^2 = 0.892$)

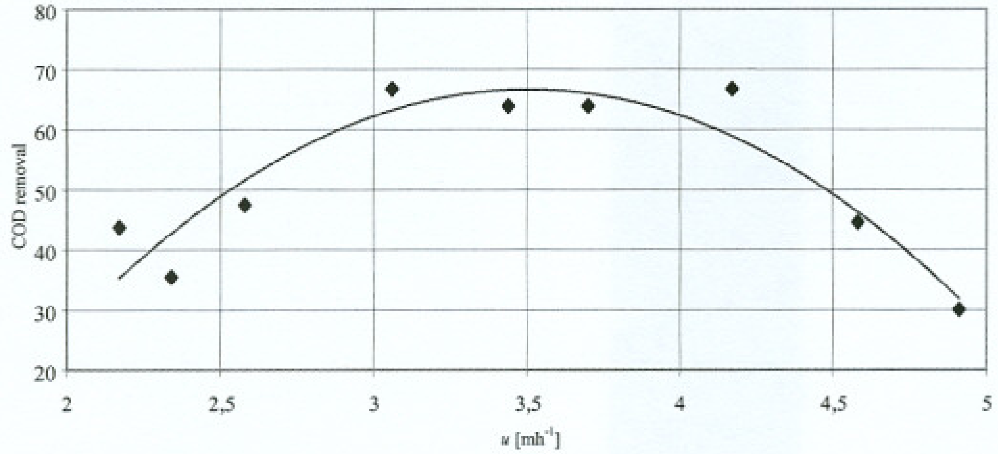

Figure 9
Removal efficiencies for filtered COD for different upflow velocities ($R^2 = 0.855$)

TABLE 3
Washout flows and filtered COD values in the effluent during Test 1

u (m h^{-1})	M_W (g 10^{-3})	m_W (%)	Filtered COD (g m^{-3})	COD removal efficiency
1	2	3	4	5
2.15	60.08	0.172	129.4	43.75
2.34	61.67	0.177	148.3	35.50
2.58	64.00	0.184	120.8	47.50
3.06	71.08	0.204	76.6	66.67
3.44	94.50	0.272	83.0	63.89
3.7	87.17	0.205	83.1	63.89
4.17	71.42	0.205	76.6	66.67
4.59	126.50	0.363	127.5	44.58
4.91	122.08	0.351	161.0	30.00

respectively). Efficiencies are likewise shown in the diagram in Fig. 9 together with the second order curve interpolating the experimental data. It can be seen that the best results correspond to values of u between 3 and 4 m·h^{-1}, with efficiency values above 60%. With lower values of u, the removal efficiencies decrease because of the formation of preferential channels for the wastewater being treated (channelling) in the sludge blanket, and although this does not give rise to washout it results in the incomplete degradation of the organic substrate. It is interesting to note that with u equal to 2.3 m·h^{-1} performance was around 40%, i.e. close to that guaranteed by the first anaerobic section of the ABR at the Biancolina WWTP with the same u (Garuti et al., 2001).

In conclusion, we can say that in the case of regular sludge blanket expansion, the upflow velocity:

- if between 3 and 4 m·h^{-1}, does not affect washout and assures very high removal efficiencies;
- for values below 3 m·h^{-1}, gives rises to negligible blanket expansion but, at the same time, results in the channelling phenomenon, which lowers treatment efficiency;
- if higher than 4 m·h^{-1}, determines a marked increase in washout and reduces performance in organic substrate removal.

Suspended solids transport modelling in sludge blanket reactors

Description of the mathematical model

The tests described in the previous paragraphs have clearly pointed out the influence of the feed conditions on the performance of expanded sludge blanket reactors. In particular, with values of D_i lower than 1 h, the sludge blanket is affected by a sort of fluidisation phenomenon appearing as a regular expansion of the granules; vice versa, with higher values of D_i it expands suddenly, giving rise to a veritable explosion of the granules when feed started. In the first case, the most convenient distribution of the time period making up the cycle can be easily determined by using a model that simulates operation of the UASBs (or each section of the ABRs), as it can reproduce: the wastewater flow to be treated; the sludge particle transport; the sedimentation of these particles in the opposite direction to that of the flow. However, it does not take into account particle transport caused by biogas as this phenomenon is negligible in the case in question.

The proposed model is based on the hypothesis that the UASB can be represented as a series of *N* completely mixed compartments of equal size. This hypothesis makes it possible to take into account the essentially one-dimensional features of the flow and also TSS concentration gradients occurring along the UASB in the absence of cohesive phenomena between the granules. Neglecting both the influent flow suspended solids content and the biosynthesis reactions, for each of the *N* compartments we can set a sludge mass balance equation expressed (with reference to the unit of surface area) by one of the following equations:

$$-u \cdot C_1 + V_{C_2} C_2 = h\frac{dC_1}{dt} \qquad (2')$$

$$u \cdot \left(C_{i-1} - C_i\right) + V_{C_{i+1}} C_{i+1} - V_{C_i} C_i = h\frac{dC_i}{dt} \qquad (2'')$$

$$u \cdot \left(C_{N-1} - C_N\right) - V_{C_N} C_N = h\frac{dC_N}{dt} \qquad (2''')$$

where:

C_i = sludge concentration (in terms of TSS and with reference to the time t) in the *i-th* compartment [$g \cdot m^{-3}$]

C_{i-1} = sludge concentration in the compartment that precedes the *i-th* one in the upflow [$g \cdot m^{-3}$]

C_{i+1} = sludge concentration in the compartment that follows the *i-th* one in the upflow [$g \cdot m^{-3}$]

C_1, C_2, C_{N-1}, C_N = sludge concentrations in the first, second, penultimate and last compartment (numbered from the bottom) of the UASB [$g \cdot m^{-3}$]

V_{C_i} = sludge settling velocity for a concentration C_i [$m \cdot h^{-1}$]

$V_{C_{i+1}}$ = sludge settling velocity for a concentration C_{i+1} [$m \cdot h^{-1}$]

V_{C_2} and V_{C_N} = sludge settling velocities corresponding to C_2 and C_N [$m \cdot h^{-1}$]

h = compartment height [m].

With reference to the *i-th* intermediate compartment, the right-hand side of Eq. (2'') represents the variation over time of the TSS mass it contains. This variation was obtained from the sum of three different contributions constituting the terms of the left-hand side of Eq. (2''): the variations in sludge particle concentration caused by the advection associated with the wastewater flow; the concentration increase caused by the sedimentation of a part of the sludge particles in the *i+1-th* compartment; and the decrease due to sedimentation in the *i-1-th* compartment. The Eqs. (2') and (2''') respectively refer to the compartments at the bottom and the surface area of the UASB and differ from Eq. (2'') in that there is a lack of the third or second contribution. In particular, the right-hand side of Eq. (2''') represents the specific contribution (per unit of surface area) to the washout of the coarser granules. The total specific washout is obtained by adding the contribution due to the colloids, which in the subsequent applications was calculated by considering a constant concentration of 70 $g \cdot m^{-3}$. Obviously the total washout is obtained by multiplying specific washout by the surface area of the UASB.

In Eq. (2) the settling velocity is a function both of the granule characteristics and of the TSS concentration (thus also including colloids). It therefore varies over time and along the UASB and was modelled in accordance with the approach proposed by Mazzolani et al. (1998):

$$V = (1 - f)V_S + f\,V_d \qquad (3)$$

where:

V_S = settling velocity in conditions of highly concentrated suspension, which is predominantly a function of the sludge particle concentration expressed by Eq. (1)

V_d = settling velocity in conditions of diluted suspension, which is solely a function of the size and nature of the particles

f = distribution factor varying in the interval 0 to 1, according to the TSS concentration.

In the absence of experimental expressions providing V_d for anaerobic sludges, the expression of Li and Ganczarick (1987) was employed in the following applications:

$$V_d = 0.35 + 1.77D \qquad (4)$$

where:

D = diameter of the sludge particles [mm]

V_d = is expressed in mm s^{-1}.

Eq. (4) was experimentally obtained with reference to aerobic activated sludge flocs with a diameter of between 0.05 and 1.40 mm. In the case in question, it was instead applied to anaerobic sludge granules considered to have a mean diameter of 2 mm (Bachmann et al., 1985). This made it possible to take implicitly into account the better sedimentation properties of anaerobic sludges.

The distribution factor was attributed with values varying according to the concentration of suspended solids. In particular, *f* was assumed to be: 0 for concentrations above 3,500 $g \cdot m^{-3}$; 1 for concentrations lower than 500 $g \cdot m^{-3}$; and linearly variable between 0 and 1 for concentrations between 500 and 3 500 $g \cdot m^{-3}$.

Applications of the mathematical model

The model illustrated in the previous section has been repeatedly used with reference to the first section of the ABR located at the Biancolina WWTP. It was first calibrated using the suspended solids measurement taken on the sludge samples from Test 3, to give the most appropriate number (*N*) of compartments arranged in series. Then the model was employed several times, varying the feed conditions, so as to assess the washout flows for each one.

Calibration was carried out by comparing the experimental measurements with the results of the model as *N* varied. This comparison showed that the most appropriate value of *N* is 6, which was then used for all subsequent simulations. This corresponds to a compartment height *h* of 0.34 m, and hence the **"1 down"** and **"1 up"** samplers belonged to the 4th and 6th compartment respectively.

Figures 10 and 11 represent, under the conditions of Test 3 carried out at the Biancolina Plant, the simulated trend of the TSS concentrations resulting in the upper layer of each of the six compartments into which the ABR section was subdivided. At start-up all biomass was considered to be at the bottom of the ABR, so that TSS concentration was held to be: 55 000 $g \cdot m^{-3}$ in the first

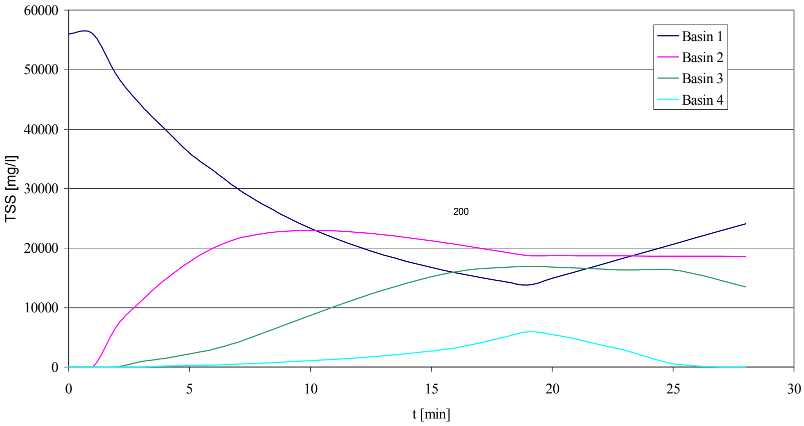

Figure 10
Trend over time of the TSS concentrations in Compartments 1, 2, 3 and 4

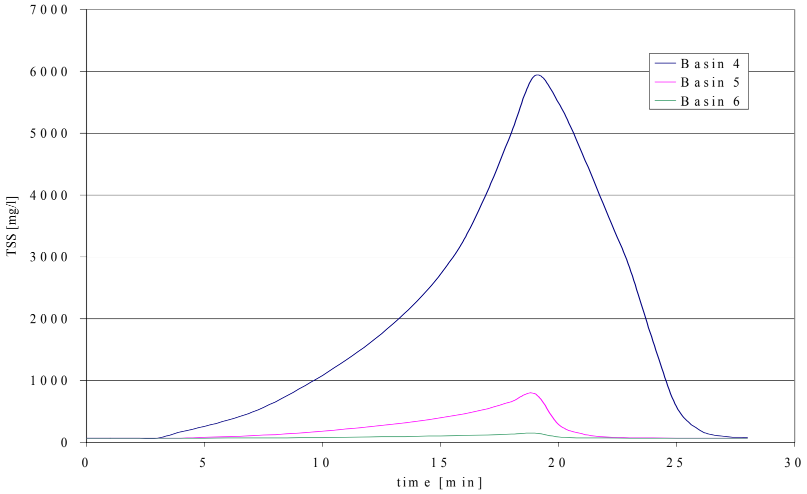

Figure 11
Trend over time of the TSS concentrations in Compartments 4, 5 and 6

TABLE 4
Operating conditions referred to in the simulations

u (m h^{-1})	D_c (min)	Numbers of cycles	D_f (min)	D_i (min)
1	**2**	**3**	**4**	**5**
2.3	68 34 17 10	21 42 84 140	20 10 5 3	48 24 12 7
3.5	68 34 17 10	21 42 84 140	20 10 5 3	48 24 12 7
4.0	68 34 17 10	21 42 84 140	20 10 5 3	48 24 12 7

compartment, i.e. equal to the value measured at the bottom of the ABR before feeding started; 70 g·m^{-3} in all the other compartments, because of the presence of colloids. As can be seen, the model follows the sludge dynamics caused by the intermittent feed; in particular, concentration in the first compartment decreases throughout the feed phase, thickening once again when lull conditions are restored. A global analysis shows that two distinct areas form in the ABR after just a few minutes from the start of feeding: the first comprises the first four compartments (and thus including the **"1 down"** sampler) and is characterised by very high TSS concentrations (above 5 000 g·m^{-3}) as it is affected by the expansion of the sludge blanket; the second consists of the remaining two compartments and the **"1 up"** sampler, and presents much smaller concentrations (less than 1 000 g·m^{-3}) which are typical of the blanket that is formed during regular expansion.

Further simulations were carried out by varying both u and D_c. In particular, three series of simulations were carried out with u values of 2.3, 3.5 and 4 m·h^{-1} (Table 4, Column 1). Each series considered four different D_c values (Table 4, Column 2), corresponding to a number of daily cycles between 21 and 140 (Column 3), and the values of D_f and D_i reported in Columns 4 and 5.

In order to point out the influence of the number of washout cycles in the ABR section, Fig. 12 refers to the case with u equal to 2.3 m·h^{-1} and reports the trend over time of the TSS concentrations in the effluent. As can be seen, concentrations fall drastically and the number of cycles increases. Particular benefits are obtained when the number of daily cycles is increased from 21 to 42. The figure clearly shows the appropriateness of the number of cycles

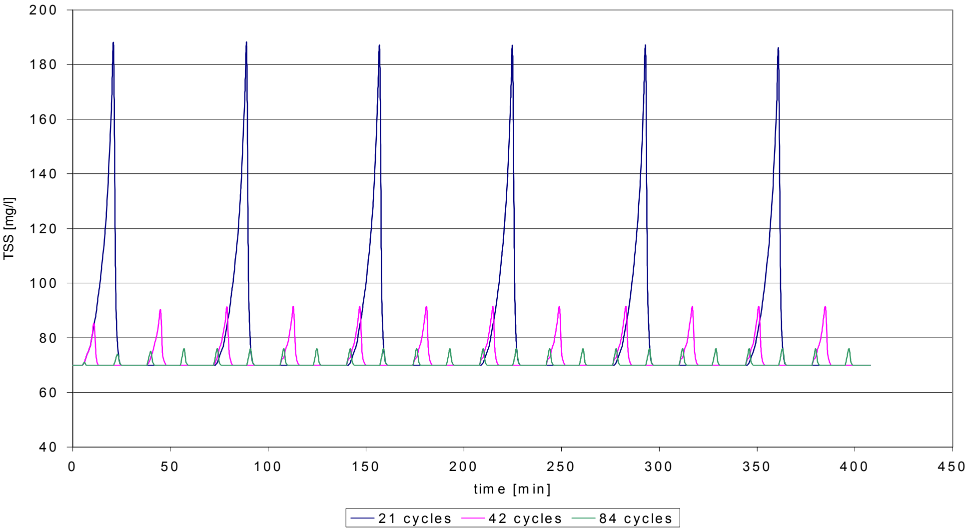

Figure 12
Trend of TSS concentrations in the effluent as the number of cycles varies, with u = 2.3 m·h⁻¹

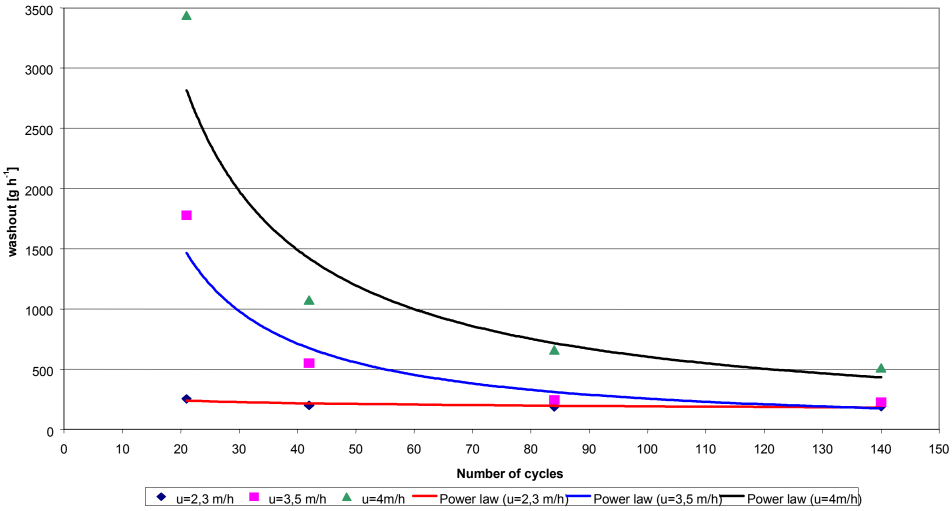

Figure 13
Washout corresponding to different feed conditions and different upflow velocities

chosen for the Biancolina plant (84) which results in limited washout.

The hourly flows of washout calculated by applying the model to the operating conditions described in Table IV are represented in Fig. 13. As can be seen, the washout increases as *u* increases. The increases are, however, markedly lower with more than 42 cycles.

Conclusions

Interest in sludge blanket anaerobic biological reactors can essentially be attributed to their low construction and running costs and the relatively high removal efficiencies they attain. Clearly their application will become more widespread only if we can fully understand the mechanisms involved in the process, both the strictly biological ones and those regarding biomass behaviour and its interaction with the incoming wastewater.

This paper has examined the dynamics of the sludge blanket when the system is intermittently fed with incoming wastewater, a condition that is extremely common in the case of treatment plants of small communities. In particular, the paper has assessed the influence of upflow velocity and feed conditions on sludge blanket expansion, a phenomenon that may arise on a regular basis or suddenly. The latter occurs when the feed flow is interrupted for long periods (above 1 h) and determines considerable losses of biomass into the effluent. With shorter periods, blanket expansion takes place on a regular basis even with very high upflow velocities (up to 4 m·h^{-1}), giving rise to limited washout and high removal efficiencies, especially with velocities ranging between 3 and 4 m·h^{-1}. These factors must, therefore, be taken into account by designers to determine the upflow velocity value. In this respect, the mathematical model proposed in the present paper can be profitably employed as it provides designers with an easy-to-use tool for assessing the most suitable ways of supplying the plant with the wastewater flow. In general, the application of this model has made it possible to determine that, in distributing the daily load to the UASBs or ABRs, it is preferable to adopt solutions involving a short duration both of the feed and the feed interruption phases, even if this entails a greater work load for the pumping equipment.

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