<http://www.diva-portal.org>

This is the published version of a paper published in *Biodegradation*.

Citation for the original published paper (version of record):

Rodriguez-Gomez, R., Renman, G., Moreno, L., Liu, L. (2014)

A model to describe the performance of the UASB reactor.

Biodegradation, 25(2): 239-251

<http://dx.doi.org/10.1007/s10532-013-9656-z>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

DOI 10.1007/s10532-013-9656-z

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-144112>

A model to describe the performance of the UASB reactor

Raúl Rodríguez-Gómez · Gunno Renman ·
Luis Moreno · Longcheng Liu

Received: 4 March 2013 / Accepted: 11 July 2013 / Published online: 23 July 2013
© Springer Science+Business Media Dordrecht 2013

Abstract A dynamic model to describe the performance of the Upflow Anaerobic Sludge Blanket (UASB) reactor was developed. It includes dispersion, advection, and reaction terms, as well as the resistances through which the substrate passes before its biotransformation. The UASB reactor is viewed as several continuous stirred tank reactors connected in series. The good agreement between experimental and simulated results shows that the model is able to predict the performance of the UASB reactor (i.e. substrate concentration, biomass concentration, granule size, and height of the sludge bed).

Keywords CSTR · Kinetic · Model · UASB · Wastewater

List of symbols

CSTR Continuous stirred tank reactor
 D_A Diffusion coefficient of substrate within the granule ($\text{m}^2 \text{h}^{-1}$)

E Inactive biomass concentration (kg m^{-3})
 K_B Saturation constant ($\text{kg COD m}^{-3} \text{h}^{-1}$)
 K_d Decay rate (h^{-1})
 K_i Inhibition constant (kg m^{-3})
 k_m Mass transfer coefficient (m h^{-1})
 K_s Half saturation concentration (kg m^{-3})
 k_s Grau second order substrate removal rate constant (h^{-1})
 N Number of CSTR
 N_p Number of granules per volume of reactor (granule m^{-3})
OLR Organic loading reate ($\text{kg COD m}^{-3} \text{h}^{-1}$)
 Pe Péclet number
 Q Flow rate ($\text{m}^3 \text{h}^{-1}$)
 q Flux ($\text{kg m}^{-2} \text{h}^{-1}$)
 R Granule radius (m)
 R_0 Initial radius of the granule (m)
 R_s Kinetic term ($\text{kg m}^{-3} \text{h}^{-1}$)
 R Radial distance from the center of the granule (m)
 S Substrate concentration (kg m^{-3})
 S_0 Inlet substrate concentration (kg m^{-3})
 S_e Effluent substrate concentration (kg m^{-3})
 S_p Substrate concentration within the granule (kg m^{-3})
 $S_{p_{\text{grad}}}$ Gradient of the substrate ($\text{kg m}^{-2} \text{h}^{-1}$)
 t Time (h)
 U_{max} Maximum utilization rate constant ($\text{kg COD m}^{-3} \text{h}^{-1}$)
 V Volume of CSTR (m^3)
 X Biomass concentration (kg m^{-3})

R. Rodríguez-Gómez · L. Moreno · L. Liu
Department of Chemical Engineering and Technology,
Royal Institute of Technology (KTH), 100 44,
Teknikringen 42, Stockholm, Sweden

R. Rodríguez-Gómez (✉) · G. Renman
Land and Water Resources Engineering, Royal Institute of
Technology (KTH), 100 44, Brinellvägen 28, Stockholm,
Sweden
e-mail: raulr@kth.se

Y	Yield [kg VSS generated (kg <i>COD</i> degraded) ⁻¹]
B	Kinetic parameter [kg <i>COD</i> (kg VSS) ⁻¹]
ϕ_P	Volume fraction occupied by the granules
ρ_{biomass}	Density of the biomass (kg m ⁻³)
μ_{max}	Maximum specific growth rate (h ⁻¹)

Introduction

The discharge of wastewater containing high concentrations of organic material is one of the main environmental problems affecting developing countries and rural areas in developed countries. In Algeria, the discharge of wastewater to the river Béchar affects the groundwater which is used as a water source for daily human activities (Abdesselema et al. 2012). In China, stormwater is mixed with urban surface runoff during its travel to the Futian river, reaching it without any treatment. The water quality of the river is thus affected by the high concentration of organic material coming via the wastewater (Lin et al. 2009). In a rural area of Manitoba, Canada, wastewater is discharged into a creek whose final destination is the Red River that flows into Lake Winnipeg. Due to the discharge of sewage, the creek water contains high concentrations of nutrients and organic pollutants, causing eutrophication problems in Lake Winnipeg (Hanson et al. 2013). In Nicaragua, the discharge of untreated wastewater to Lake Cocibolca has caused eutrophication problems; affecting the aquatic life (Vammen et al. 2012).

These environmental problems can be prevented if pollutants such as organic matter are removed from the wastewater. The Upflow Anaerobic Sludge Blanket (UASB) reactor is an attractive option that is widely used to remove organic matter from wastewater. It is an anaerobic process in which the organic matter is removed by the action of microorganisms. This technology can be used to treat both industrial and domestic wastewater (Khanh et al. 2011) and provides the following advantages: the maintenance and operating costs are relatively low compared with those of aerobic processes; it does not need any support media for the development of the microorganisms since the hydraulics in the reactor induce the formation of dense granules, which are kept in the lower part of the reactor (Wang et al. 2011); it removes the organic material and also generates biogas that can be used as an energy

source, due to its methane content (Angelidaki et al. 2011); and the growth rate of the biomass is low, hence a discharge of biomass takes place after a long time of operation (Seghezzi 2004). The main disadvantage of the UASB reactor is that start-up may take a long time, especially when the reactor is inoculated with sludge instead of dense granules. The sludge tends to be dragged by the flow of wastewater to the outlet of the reactor. However, there are many publications describing ways to achieve successful start-up of the reactor (Ahmad et al. 2011) and this technology is continually being improved.

The principal function of the UASB reactor is the treatment of wastewater containing easily hydrolysable substrate, but it has also been tested in the treatment of complex substrates with satisfactory results. Additionally, the UASB reactor has been used for the purpose of generating biogas of differing composition, such as methane or hydrogen (Abbasi and Abbasi 2012).

The formation of granules is the key to successful performance of a UASB reactor (Hulshoff et al. 2004). This issue has been widely studied by researchers and several theories have been proposed to describe the formation of granules, comprising physical, microbial, and thermodynamic phenomena. Physically-based theory states that the granules are initially formed by fine particles containing microorganisms and that the flow of water causes movement of these fine particles. Inevitably, two or more particles collide and attach themselves, forming the core of the granule. This process is repeated several times, and the size of the aggregate grows, creating the granule. Hence, the sum of the hydraulic load and the load caused by gas generation is reported to play an important role in granulation in the UASB reactor (Hulshoff et al. 2004; Flaherty et al. 2003; Liu et al. 2003; Pereboom 1994a, b). Microbial-based theories hold that the microbial population secretes extracellular polymers (ECP) which act as glue and protect the microorganisms against shear stress in the reactor. Therefore, the microorganisms adhere to themselves and trap dispersed microorganisms in their sticky structure, forming a granule. The main microbial theories are: spaghetti theory, the Capetown model, and the extracellular polymer (ECP) bonding model (Hulshoff et al. 2004; Liu et al. 2003; Palns et al. 1987). Thermodynamic-based theories involve processes of adsorption, proton translocation, and electrostatic interaction

between charged bacteria (McHugh et al. 2003; Tay et al. 2000; Liu et al. 2003). For instance, according to the four-step model for granulation developed by Ahring and Schmidt (1996): (1) a cell is transported to another cell or other inert material, (2) an irreversible adsorption phase occurs, (3) cells adhere to each other by polymer attachment, and (4) cells multiply, thus generating granules.

These theories have been developed to explain the mechanism of granule formation. However, there are factors that influence granule characteristics, such as pH, temperature, organic loading rate, hydraulic retention time, up-flow velocity, type of substrate, and microorganism source. For a comprehensive explanation of these factors, see Rodríguez-Gómez (2011). When these factors work properly, the microorganisms degrade the substrate through a series of bio-reactions and convert it into biogas. The microorganisms acting in these bio-reactions are classified into three groups: acidogenics, acetogenics, and methanogenics (MacLeod et al. 1990). However, the anaerobic digestion of complex polymer materials requires seven processes (Seghezzo 2004). Hydrolysis is the first process and some researchers have reported that it is the rate-limiting step in the bioconversion of the substrate (Graaff et al. 2010; Foresti et al. 2006; Lew et al. 2004; Aiyuka et al. 2004; Mahmoud et al. 2003). In a study on the kinetics of hydrolysis in anaerobic digestion, Flotats et al. (2008) presented kinetic models (i.e. Contois, Michaelis–Menten, etc.) that include the hydrolysis reaction as the limiting process for the degradation of the substrate and the growth of the microorganisms. However, the kind of substrate used in the UASB reactor plays an important role in identifying the reaction controlling the conversion of the substrate (Zhou et al. 2006). Acidogenic, acetogenic, and methanogenic microorganisms have also been reported to be limiting factors in anaerobic digestion (Tiwari et al. 2006; Chou and Huang 2005; Huang et al. 2004a; Huang et al. 2004b; Hutnán et al. 1999).

The degradation of the substrate is solely attributable to the kinetics in the granule, a reaction which is very important for the successful functioning of the UASB reactor. To describe the reaction rate (i.e. kinetics) in the granules, some models have been proposed, the most popular being the Monod model, which has been widely used with successful results (Sponza and Uluköy 2008; Kryłów 2003). It states that

the growth rate of the microorganisms is zero when there is no substrate and it reaches a maximum when there is an excess of substrate (Lorby et al. 1992). Based on the Monod model, the Contois model was developed. The main difference is that Contois model assumes that the growth rate of the biomass depends on the concentrations of both the substrate and microbial populations, while the Monod model takes only the former into account (Contois 1959). Another kinetic model is the modified Stover–Kincannon model, which utilizes the total organic loading rate as the key parameter to describe the kinetics in the UASB reactor (Yetilmezsoy 2012; Sponza and Uluköy 2008). Table 1 shows the most important kinetics models describing the degradation of the substrate. Those models can also describe the growth of biomass in the UASB reactor if the parameter expressing the amount of biomass generated by amount of substrate consumed (i.e. yield) is adjusted.

Kinetic models have been coupled with dynamic models to predict the removal of substrate and the growth in biomass concentration in the UASB reactor. For instance, the Grau model is based on the linear removal concept, which is a phase of the Monod model (Sponza and Isik 2005; Grau et al. 1975).

Wu and Hickey (1997) proposed a model to describe the consumption of substrate in the UASB reactor. It includes the mass transfer and the diffusion of the substrate within the granule. The size of the granule is assumed to be constant in the model. However, simulations that involve varying the size of the granule indicate that the performance of the UASB reactor is significantly sensitive to this parameter (Wu and Hickey 1997).

Table 1 Kinetics models used to describe degradation of the substrate in the UASB reactor

Name of the model	Equation	Equation number
Monod (Lorby et al. 1992)	$\frac{dS}{dt} = -\frac{\mu_{max}}{Y} \cdot \frac{X \cdot S}{K_s + S}$	(1)
Contois (Contois 1959)	$\frac{dS}{dt} = -\frac{\mu_{max}}{Y} \cdot \frac{X \cdot S}{\beta \cdot X + S}$	(2)
Modified Stover–Kincannon (Yetilmezsoy 2012)	$\frac{dS}{dt} = -\frac{U_{max} \cdot OLR}{K_B + OLR}$	(3)
Second-order Grau (Sponza and Isik 2005)	$\frac{dS}{dt} = -k_S \cdot X \cdot \left(\frac{S}{S_0}\right)^2$	(4)
Haldane (Ghangrekar and Bhunia 2008)	$\frac{dS}{dt} = -\frac{\mu_{max}}{1 + \frac{K_S}{S_e} + \frac{S}{K_i}} \cdot \frac{X}{Y}$	(5)

Rodríguez-Gómez et al. (2013) developed a model describing the kinetic rate in the UASB reactor that takes into account the change in granule size. Hence, the kinetic term also changes with time. However, the substrate conversion rate within the granule is assumed to be constant.

The main problem with the existing dynamic models is that they are complex, including many parameters which are not always easy to measure experimentally (Kalyuzhnyi et al. 2006; Batstone et al. 2002). However, simple models omit some important processes (Sponza and Uluköy 2008; Wu and Hickey 1997; Narnoli and Mehrotra 1997), such as the mass transport resistance that the substrate encounters before its biotransformation.

The aim and scope of this study is to develop a kinetic expression including the mass transport resistances experienced by the substrate along its path into the core of the granule. This expression takes into account the change in granule size with time, and the Monod equation is used to describe the biotransformation of the substrate in the reaction occurring within the granule. This kinetic expression is then used as the kinetic term in a dynamic model describing the behavior of the UASB reactor (i.e. tanks in series model). With this, the concentration of substrate and biomass and the change in granule size with time in the UASB reactor can be predicted.

In “[Conceptual model](#)” section the theoretical basis is addressed, in which the development of the kinetic expression is explained. The governing equations for the UASB reactor are then shown, with their kinetic term represented by the kinetic expression. In addition, a short explanation of a case study taken from the literature is presented and the data used to validate the model. Results and discussion are presented in “[Results and discussion](#)” section, which is divided into three parts: (1) Comparison of simulated and measured data, (2) capability of the model, and (3) sensitivity analysis. Finally, the “[Conclusions](#)” section is presents.

Conceptual model

The UASB reactor is charged with granulated anaerobic microorganisms, which form the sludge bed. The inlet of the substrate is located at the bottom of the UASB reactor. The substrate is composed of organic

material and it is digested by the microorganisms, generating new cells and biogas from the core of the granule (MacLeod et al. 1990).

This generation of biogas affects the density of the granules. Consequently, an uplift force is experienced by the particles, which are dragged to the upper part of the reactor (Ng et al. 2006). This occurs due to biogas trapped within the granule and/or attached bubbles of biogas on the granule surface, which induce buoyancy on the particles. A gas–solid separator is located at the top of the reactor, where the biogas is released and the particles fall down (Luo and Al-Dahhan 2011; Bhattacharyya et al. 2009; Liu and Tay 2002). The granules are thus constantly moving up and down in the reactor. For the sake of simplicity, we assumed that the granules are of a similar size in the sludge bed, but that they grow with time.

A maximum fraction of sludge ϕ_{pmax} is assumed in the sludge bed of the UASB reactor. This takes into consideration the porosity of the granules (Alphenaar et al. 1992) and the space between them (i.e. space occupied by wastewater). When the amount of biomass exceeds ϕ_{pmax} , the excess of biomass uplifts. Consequently, the sludge bed expands with time. Hence, the expected biomass profile along the height of the UASB reactor is as described by Narnoli and Mehrotra (1997) (Fig. 1).

The biomass is composed of active and inactive microorganisms. However, decay of the microorganisms may occur due to the presence of toxic compounds (Kryłow 2003), predation (Bitton 2005), and lysis (Kalyuzhnyi et al. 2006). This means that inactive biomass is constantly appearing due to decay, while reproduction of microorganisms results in an increase in active biomass. Consequently, the sludge

Fig. 1 Profile of the biomass along the height of the reactor (adapted from Narnoli and Mehrotra 1997)

bed expands until a discharge of biomass is necessary (Seghezzi et al. 2002).

The biomass in the UASB reactor is present in the form of granules. Inside these granules, degradation of the substrate occurs. Researchers agree that there is a particular process which controls the reaction. Here we assumed that the degradation of the substrate is controlled by one process (i.e. the rate-limiting step) and it is described by the Monod model. However, the kinetics may be described by another kinetic model. The choice of kinetic equation depends on the type of substrate and researchers must use the most appropriate for the reactor, based on experience or the history of the UASB reactor. In the present case Monod is used because it has been widely applied to describe the kinetics of wastewater originating from slaughterhouses (Massé and Masse 2000; Borja et al. 1994).

In this paper, the UASB reactor is viewed as several continuous stirred tanks of equal volume connected in series. This allows the different processes occurring along the height of the reactor to be studied as the concentrations of biomass and substrate vary. The number of reactors (N) takes into account the degree of mixing in the UASB reactor. It is related to the Péclet (Pe) number as (Saravanathamizhan et al. 2010; Fogler 2006; Abu-Reesh and Abu-Sharkh 2003):

$$N = (Pe/2) + 1 \quad (6)$$

As Eq. (6) indicates, greater dispersion occurs if the UASB reactor is divided into few CSTR (i.e. low Péclet number). On the contrary, plug flow behavior can be expected with a large number of reactors (i.e. high Péclet number).

Governing equations

Within the granule (Fig. 2), it is possible to identify two resistances to conversion of the substrate: (1) Transport of the substrate through the stagnant liquid film, and (2) transport by diffusion and biotransformation of the substrate (i.e. reaction).

A quasi-steady state mass balance for the concentration of substrate in the granule is applied, since the amount of substrate degraded in a time interval is much greater than the variation in substrate in the granule in the same time interval:

$$D_A \frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dS_p}{dr} \right) = -R_S \quad (7)$$

Fig. 2 Representation of a granule. **a** Transport of the substrate through the stagnant liquid film, and **b** transport by diffusion and biotransformation of the substrate within the granule

R_S is the kinetic term, and it is assumed that it follows the Monod equation:

$$\left(i.e. R_S = -\frac{\mu_{max}}{Y} \cdot \frac{X}{K_S + S_p} \cdot S_p \right) \quad (8)$$

$$D_A \frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dS_p}{dr} \right) - \frac{\mu_{max}}{Y} \cdot \frac{X}{K_S + S_p} \cdot S_p = 0$$

The boundary conditions are:

$$-D_A \frac{dS_p}{dr} \Big|_{r=R} = k_m (S - S_p|_{r=R}) \quad (9)$$

$$S_p|_{r=0} = \text{finite} \quad (10)$$

Equation (8) describes the degradation of the substrate within the granule as a function of the microbial population and the granule size (i.e. kinetic rate).

Chou and Huang (2005) reported that external mass transfer (i.e. transfer of substrate from the bulb liquid to the particle surface) is of minor relevance for the removal of substrate. Similarly, Gonzalez-Gil et al. (2001) studied the influence of internal and external mass transfer in the Monod model and concluded that external mass transfer can normally be neglected. Consequently, Eq. (9) gives $S = S_p|_{r=R}$. From that, the gradient of the substrate along the radial distance of the granule $S_{p,grad}$ is known. Hence, the flux (q) can be obtained by multiplication of ($S_{p,grad}$) by the diffusion coefficient (D_A). The reaction term (R) can thus be described as:

$$R = q \cdot 4\pi r^2 \cdot N_p \quad (11)$$

where the left-hand term represents the amount of substrate degraded (inside the granule) in units of volume and of time. Therefore, this expression is

Fig. 3 UASB reactor depicted as many continuously stirred tank reactors (CSTR) connected in series; **a** UASB column, **b** CSTR at different heights of the UASB column, **c** i and $i + 1$ -reactors

coupled with the governing equations describing the change in concentration of both the substrate and the biomass in the UASB reactor.

The three equations controlling the behavior of the UASB reactor describe: the concentration of the substrate, the concentration of active biomass, and the concentration of inactive biomass for each small reactor (Fig. 3).

The equations for the i -reactor are:

$$\frac{dS_i}{dt} = \frac{Q}{V_i} \times (S_{i-1} - S_i) - R_i \quad (12)$$

$$\frac{dX_i}{dt} = R_i \times Y - K_d \times X_i \quad (13)$$

$$\frac{dE_i}{dt} = K_d \times X_i \quad (14)$$

where the term on the left-hand side corresponds to the accumulation of substrate, active biomass, and non-active biomass in equation 12, 13 and 14, respectively. Dispersion is not included in these equations, since it is taken into account by the number of small reactors.

In Eq. (12), the first term on the right-hand side is the advective term and the second one is the reaction term. The reaction rate in Eqs. (12) and (13) corresponds to the expression described in Eq. (11). This means that the reaction rate changes in every interval of time; thus a new kinetic value is calculated continuously. The terms on the right-hand side of Eq. (13) correspond to the biomass generation and decay

rates, respectively. The number of granules, which is assumed to be constant, is determined by:

$$N_p = \frac{X + E}{\rho_{biomass}} \cdot \frac{1}{\frac{4}{3} \cdot \pi R_0^3} \quad (15)$$

Therefore, the radius of the granule can be determined by simply rearranging Eq. (15). In the previous section, the governing equations describing the performance of the UASB reactor were shown. These governing equations are nothing but systems of parabolic and elliptic partial differential equations (i.e. pdepe) and the software used to obtain the solution is Matlab. In the following, a practical case is used to run the model is briefly explained.

Case study

The performance of a UASB reactor treating wastewater coming from a slaughterhouse was studied by Nacheva et al. (2011). After a pretreatment to eliminate large particles and fat, the wastewater was fed into the UASB reactor (a column with effective volume 0.015 m^3 and internal diameter 0.15 m). The reactor was inoculated with granular sludge from a full-scale UASB reactor treating sugar cane wastewater and acclimatized with the wastewater coming from the slaughterhouse. Data used in the simulation are shown in Table 2. The diffusion coefficient used in the model is a typical value for granules in UASB reactors and it was taken from literature (Lens et al. 2003), as

Table 2 Data used in the simulations

Entity	Value	Units
Height of the column	1.3	m
Yield	0.07	–
Decay rate constant, K_d	1.4E-03	h^{-1}
Diff. coeff. in the particle, D_A	4.7 E-06	$\text{m}^2 \text{h}^{-1}$
Density of sludge, ρ_{biomass}	1,026	kg m^{-3}
Half velocity coeff., K_s	0.372	kg m^{-3}
Max. specific growth rate, μ_{max}	0.027	h^{-1}
Max. biomass in every reactor, ϕ_{Pmax}	25	%

was the value used for density of the biomass (Pereboom 1994a, b), since these parameters were not reported by Nacheva et al. (2011). The kinetics parameters were determined using the method described by Richardson and Peacock (1994) and the calculations were based on data reported by Nacheva et al. (2011). However, the yield was adjusted in the model in order to be consistent with the removal of the COD in the first stage of the experiments. The calculated value of yield was 0.093 and the adjusted value 0.07.

Nacheva et al. (2011) divided their experimental work into four stages, each with different inlet substrate loading rates (i.e. 4, 7, 10, and 15 $\text{kg COD m}^{-3} \text{d}^{-1}$) in the facility. The upflow velocity in the UASB reactor was 0.05, 0.062, 0.1, and 0.146 m h^{-1} , and the operation time was 151, 110, 91, and 91 d for stages 1, 2, 3, and 4, respectively.

In the model, it is assumed that every CSTR contains a maximum amount of biomass (ϕ_{Pmax}), corresponding to 25 % of the volume of the CSTR. Once the results from the first stage are known, they are used as input data for the second stage and so on.

Simulated cases

The cases shown comprise three sets of simulations using data from Nacheva et al. (2011). In the first set of

simulations the experimental data were used to validate the model. The simulation was run for stage 1, and then the results of stage 1 were used as input in stage 2, and so on. The resulting removal of substrate (as COD) was compared with the experimental data.

In the second set of simulations, the conditions from stage 2 in Nacheva et al. (2011) were used and this set was run to show the capability of the model. The substrate concentration, concentrations of active and non-active biomass, and the granule size as a function of time are shown. The advance of the front between the sludge bed and the blanket is also presented.

Finally, an analysis of sensitivity was carried out. A parameter that has a great influence on the results should be determined with a high certainty, while a rough approximation may be sufficient for a parameter with a low influence on the results.

Results and discussion

Comparison of experimental and simulated results

To validate the model, simulated and experimental results were compared. Parameter values used in the simulation were those used by Nacheva et al. (2011) and the comparison was made with the mean values obtained in the experimental part.

The percentage removal of the substrate in stage 1 was adjusted to fit the experimental data. The value of yield was manipulated to achieve a COD removal of 76.2 % in stage 1. The results (i.e. concentration of biomass and granule size) at the end of a stage were used as input values to the next stage. Table 3 shows the upflow velocities, times intervals, and the percentage of removal of the substrate from the experimental and simulated parts for every stage.

Figure 4 shows a comparison of the experimental and simulated results for removal of the substrate. It includes maximum, minimum, and mean values of

Table 3 Experimental and simulation results

Entity	Stage 1	Stage 2	Stage 3	Stage 4
Upflow velocity, [$\text{m}^3 \text{m}^{-2} \text{h}^{-1}$]	0.05	0.062	0.100	0.146
Time interval, [days]	0–151	152–262	263–54	355–446
Experimental removal of COD, [%]	76.2 $\pm$ 8.0	83.9 $\pm$ 5.4	87.4 $\pm$ 2.0	89.9 $\pm$ 1.1
Simulated removal of COD, [%]	76.2	84.6	88.0	90.7

Fig. 4 Comparison of experimental and simulated results—Experimental results (maximum, mean, and minimum); o: Simulation results

removal of substrate reported by Nacheva et al. (2011). As can be seen, the model response shows good agreement with the experimental results and the values are in the range of the results (i.e. goodness of fit) reported by Nacheva et al. (2011).

The efficiency of removal of the substrate in the model response is similar to the experimental value. The percentage substrate removal tends to increase from one stage to another, which can be attributed to the upflow velocity increasing from one stage to another. Korsak (2008) demonstrated that high upflow velocities improve the interaction area between substrate and microorganisms, since they (in addition to biogas) induce agitation in the sludge bed. Consequently the removal of the substrate increases. However, high velocities can also result in washout of the biomass (Korsak 2008).

So far we have seen that the model predicts the removal of the substrate in an acceptable way. However, the model has other capabilities, which are presented in the next section.

Capability of the model

Besides the concentration of substrate, the model is able to describe the behavior of other parameters, such as: the height of the sludge bed, the concentration of active, inactive, and total biomass, the distribution of the biomass along the height of the reactor, and granule size over time. These capabilities are addressed in this section.

Data from stage 2 of Nacheva et al. (2011) were taken to demonstrate the capability of the model. However, the operating time was extended to 1.5 years in order to have growth of biomass and show the expansion of the sludge bed. The operating time of the UASB reactor was divided into four intervals to show the profile of the concentration of substrate at different times.

Figure 5a shows the profile of the substrate concentration along the 16 CSTR (i.e. the height of the UASB reactor) connected in series. After 135 days, the percentage COD removal reached 92 % and it increased continuously until 97 % at the last time.

Figure 5b shows the fraction of biomass (ϕ_P) contained in every CSTR, provided $\phi_{Pmax} = 25$ %. When a CSTR reaches ϕ_{Pmax} , the surplus goes to the next reactor, and so on. The behavior of the ϕ_P parameter provides information about the increase in height of the sludge bed in the UASB reactor. After the first time interval (i.e. 135 days), the sludge bed is composed of three CSTR, plus one partially filled (i.e. it has not even reached ϕ_{Pmax}). While time passes, biomass is generated due to reproduction of the microorganisms and the sludge bed is thus expanding. In the last interval (i.e. 540 days), the sludge bed comprises 12 CSTR. At this time, discharge of sludge is probably necessary.

Figure 5c shows the distribution of the active biomass along the height of the UASB reactor (i.e. CSTR series). The active biomass increases and passes from one CSTR to another. In every time interval, the concentration of the active biomass decreases in the reactor_i. This occurs due to the effect of the decay rate. However, new biomass appears constantly and when the reactor_i reaches ϕ_{Pmax} , the new active biomass passes to reactor_{i+1}. After the first time interval (i.e. 135 days), the amount of active biomass in the UASB reactor is 0.190 kg, but with time it increases up to 0.225 kg in the last time interval (i.e. 540 days). The active biomass behaves similarly to the distribution of biomass described in Narnoli and Mehrotra (1997) (Fig. 1).

From Fig. 5b, c, the Péclet number can be determined using equation (6). Despite the UASB reactor being divided into 16 CSTR, the Péclet number is determined as a function of the height of sludge bed (i.e. number of CSTR filled). At the beginning, three CSTR form the sludge bed, but the number of CSTR increases with time. This means that initially the

Fig. 5 Simulation response. **a** Substrate concentration along the height of the UASB reactor, **b** fraction of biomass contained in every CSTR, and **c** distribution of active biomass along the height of the UASB reactor, where *Large circle* = 135 days,

asterisk = 270 days, *Lozenge* = 405 days, *Star* = 540 days. **d** change in concentration of active (*Large circle*), inactive (*asterisk*), and total (*Lozenge*) biomass with time

Fig. 6 Granule size as a function of time

UASB reactor has high dispersion, since Péclet number is low (flow behaves as “complete mixing”). Gradually, the flow tends to become “plug flow” due to the expansion of the sludge bed (more CSTR form the sludge bed), which increases the Péclet number. Hence, in this case, the flow ranges between completes mixing and plug flow.

The change in concentration of the active, inactive, and total biomass with time is shown in Figs. 5d. Initially the concentration of the total biomass is 29 kg m⁻³, but it reaches values of 31.92, 33.45, 33.94, and 34.16 kg m⁻³ for 135, 270, 405, and 540 days, respectively.

The granule is composed of active and inactive biomass. Initially, the average radius is assumed to be 0.25 mm, but it increases with time due to the generation of biomass. Figure 6 shows the growth of the granule radius for time intervals of 20 days, reaching a diameter of 1.2 mm after 540 days.

As shown above, the model is a useful tool to obtain information about the efficiency of removal of substrate, production of biomass, height of the sludge bed, and size of the granules in the UASB reactor. A sensitivity analysis was performed on the main parameters of the model, as described below.

Sensitivity analysis

A sensitivity analysis examined the effects of changing the number of CSTR (N), the diffusion coefficient

Fig. 7 Results of the sensitivity analysis for **a** number of small reactors, **b** diffusion coefficient, **c** maximum amount of biomass in every CSTR, and **d** yield value

(D_A), the maximum amount of biomass permitted in each CSTR ($\phi_{P_{\max}}$), and the yield. This was done using data from stage 2 of the Nacheva et al. (2011) experiments. However the working time of the UASB reactor was extended to 1 year. In order to determine how the reactor behaves when the parameters vary (i.e. N , D_A , $\phi_{P_{\max}}$, yield), one parameter was varied leaving the other two constant and the percentage substrate removal was plotted as a function of this.

As Fig. 7a shows, the removal of the substrate concentration with different values of N ranged between 93 and 98 % when N was given values between 8 and 70. The values of N used in the simulation ranged more widely than the values given by the model (i.e. percentage substrate removal). Therefore, the number of reactors into which the UASB reactor is divided has little effect in the model.

The removal of the substrate was strongly affected by low diffusion coefficient values (Fig. 7b). However, when the diffusion coefficient was high, the substrate removal remained constant and the particular value used for the diffusion was not relevant. The substrate removal varied from 69 to 96 % for values of

diffusion coefficient between $1\text{E} - 8 \text{ m}^2 \text{h}^{-1}$ and $3\text{E} - 7 \text{ m}^2 \text{h}^{-1}$.

According to Huang et al. (2003) and Kalyuzhnyi et al. (2001), the value of $\phi_{P_{\max}}$ is as high as 35 %. In the sensitivity analysis the value of $\phi_{P_{\max}}$ was varied between 18 and 40 %. The results (i.e. 97–94 % of substrate removal, respectively) showed there was no major difference for different values of $\phi_{P_{\max}}$ (Fig. 7c) This is because the amount of biomass is always the same in the UASB reactor. The value of $\phi_{P_{\max}}$ affects only the height of the sludge bed.

The yield is an important parameter due to the high sensitivity of the model response. Low values of yield represented little active biomass, so the removal of substrate was low. However, when the value of the yield was increased, the removal of the substrate increased significantly (Fig. 7d).

According to the sensitivity analysis, the parameters that most influence the performance of the UASB reactor are diffusion coefficient and yield. For small values of diffusion coefficient, the removal of the substrate varied strongly. However, the substrate removal remained constant at high values, which

means that the process is controlled by another factor. Rodríguez-Gómez et al. (2013) reported that the mass transfer coefficient controls the behavior of the UASB reactor when the diffusion coefficient takes high values. $\phi_{P_{\max}}$ and N are helpful in understanding the phenomenon of expansion of the sludge bed in the reactor and also give an idea of how the flow in the UASB reactor behaves, i.e. ranging from complete mixing to plug flow.

Conclusions

The model developed here is able to simulate the change in substrate concentration, biomass concentration, height of the sludge bed, and granule size in the UASB reactor. The model includes terms for dispersion, advection, and reaction.

The reaction is described by an expression developed in this paper and the kinetics follows the Monod model. The expression describing the reaction term is solved in a numerical way and takes into account the resistances through which the substrate passes before its biotransformation.

Due to the fact that only the most important processes are taken into account in the model, few parameters are necessary to simulate the UASB reactor process. The model successfully simulated the behavior of a real UASB reactor treating wastewater from a slaughterhouse according to a comparison of simulated and measured data.

A sensitivity analysis revealed that diffusion of the substrate within the granule and yield plays an important role for prediction of substrate removal from the UASB reactor.

References

- Abbasi S, Abbasi T (2012) Formation and impact of granules in fostering clean energy production and wastewater treatment in upflow anaerobic sludge blanket (UASB) reactors. *Renew Sustain Energy Rev* 16:1696–1708
- Abdesselema K, Azedineb H, Lyndac C, Younesa S (2012) Wastewater discharge impact on groundwater quality of Béchar city, southwestern Algeria: an anthropogenic activities mapping approach. *Procedia Eng* 33:242–247
- Abu-Reesh Abu-Sharkh (2003) Comparison of axial dispersion and tanks-in-series models for simulating the performance of enzyme reactors. *Ind Eng Chem Res* 42:5495–5505
- Ahmad A, Latif M, Ghufuran R, Wahid Z (2011) Integrated application of upflow anaerobic sludge blanket reactor for the treatment of wastewaters. *Water Res* 45:4683–4699
- Ahring B, Schmidt J (1996) Review granular sludge formation in upflow anaerobic sludge blanket (UASB) reactors. *Biotechnol Bioeng* 49:229–246
- Aiyuka S, Amoakoa J, Raskin L (2004) Removal of carbon and nutrients from domestic wastewater using a low investment, integrated treatment concept. *Water Res* 38:3031–3042
- Alphenaar P, Perez C, van Berkel W, Lettinga G (1992) Determination of the permeability and porosity of anaerobic sludge granules by size exclusion chromatography. *Appl Microbiol Biotechnol* 36:795–799
- Angelidaki I, Fang C, Boe K (2011) Biogas production from potato-juice, a by-product from potato-starch processing, in upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors. *Bioresour Technol* 102:5734–5741
- Batstone D, Keller J, Angelidaki I, Kalyuzhnyi S, Pavlostathis S, Rozzi A, Sanders W, Siegrist H, Vavilin V (2002) Anaerobic digestion model No.1 (ADM1), by IWA task group for mathematical modeling of anaerobic wastewater process. Scientific and technical report No. 13. International water association (IWA) Publishing, London
- Bhattacharyya D, Harmita H, Singh K, Wilson B (2009) Fluidization in an anaerobic EGSB reactor: analysis of primary wakes and modeling of sludge blanket. *J Environ Eng* 135:700–707
- Bitton G (2005) Wastewater microbiology. Wiley-Liss, Hoboken
- Borja R, Banks C, Wang Z (1994) Performance and kinetics of an upflow anaerobic sludge blanket (UASB) reactor treating slaughterhouse wastewater—part A: toxic hazardous substances and environmental engineering. *J Environ Health* 29:2063–2085
- Chou H, Huang J (2005) Role of mass transfer resistance in overall substrate removal rate in upflow anaerobic sludge bed reactors. *J Environ Eng* 131:548–556
- Contois D (1959) Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures. *J Gen Microbiol* 21:40–50
- Flaherty V, McHugh S, Reilly C, Mahony E, Collieran E (2003) Anaerobic granular sludge technology. *Environ Sci Bio/Technol* 2:225–245
- Flotats X, Vavilin V, Fernandez B, Palatsi J (2008) Hydrolysis kinetics in anaerobic degradation of particulate organic material: an overview. *Waste Manag* 28:939–951
- Fogler HS (2006) Chemical reactor engineering. Amundson, Huston
- Foresti E, Zaiat M, Vallero M (2006) Anaerobic processes as the core technology for sustainable domestic wastewater treatment: consolidated applications, new trends, perspectives, and challenges. *Rev Environ Sci Bio/Technol* 5:3–19
- Ghangrekar M, Bhunia P (2008) Analysis, evaluation, and optimization of kinetic parameters for performance appraisal and design of UASB reactors. *Bioresour Technol* 99:2132–2140
- Gonzalez-Gil G, Seghezzi L, Lettinga G, Kleerebezem R (2001) Kinetics and mass-transfer phenomena in anaerobic granular sludge. *Biotechnol Bioeng* 73:125–134

- Graaff M, Temmink H, Zeeman G, Buisman C (2010) Anaerobic treatment of concentrated black water in a UASB reactor at a short HRT. *J Water* 2:101–119
- Grau P, Dohányos M, Chudoba J (1975) Kinetics of multi-component substrate removal by activated sludge. *Water Res* 9:637–642
- Hanson M, Carlson J, Anderson J, Low J, Cardinal P, MacKenzie S, Beattie S, Challis J, Bennett R, Meronek S, Wilks R, Buhay W, Wong C (2013) Presence and hazards of nutrients and emerging organic micropollutants from sewage lagoon discharges into Dead Horse creek, Manitoba, Canada. *Sci Total Environ* 445–446:64–78
- Huang J, Jih C, Lin S, Ting W (2003) Process kinetics of UASB reactors treating non-inhibitory substrate. *J Chem Technol Biotechnol* 78:762–772
- Huang J, Chou H, Hong W (2004a) Temperature dependency of granule characteristics and kinetic behavior in UASB reactors. *J Chem Technol Biotechnol* 79:797–808
- Huang G, Hsu S, Liang T, Huang Y (2004b) Study on hydrogen production with hysteresis in UASB. *Chemosphere* 54: 815–821
- Hulshoff L, Lens P, Castro S, Lettinga G (2004) Anaerobic sludge granulation. *Water Res* 38:1376–1389
- Hutñán M, Mrafková L, Drtil M, Derco J (1999) Methanogenic and nonmethanogenic activity of granulated sludge in anaerobic baffled reactor. *Chem Papers* 53:374–378
- Kalyuzhnyi S, Fedorovich V, Lens P (2001) Novel dispersed plug flow model for UASB reactors focusing on sludge dynamics in anaerobic digestion. *Proc Antwerpen, Belgium* 123–128
- Kalyuzhnyi S, Fedorovich V, Lens P (2006) Dispersed plug flow model for upflow anaerobic sludge bed reactors with focus on granular sludge dynamics. *J Ind Microbiol Biotechnol* 33:221–237
- Khanh D, Quan L, Zhang W, Hira D, Furukawa K (2011) Effect of temperature on low-strength wastewater treatment by UASB reactor using poly(vinyl alcohol)-gel carrier. *Bioresour Technol* 102:11147–11154
- Korsak L (2008) Anaerobic treatment of wastewater in a UASB reactor. Dissertation, Royal Institute of Technology
- Kryłów M (2003) Kinetics of subsequent phases of the anaerobic processes. *Proc of a Polish-Swedish seminar*. In: Plaza E, Levlin E, Hultman B (ed) *Integration and optimisation of urban sanitation systems*. Wisla pp 29–37
- Lens P, Gastesi R, Vergeldt F, van Aelst A, Pisabarro A, Van As H (2003) Diffusional properties of methanogenic granular sludge: ^1H NMR characterization. *Appl Environ Microbiol* 69:6644–6649
- Lew B, Tarre S, Belavski M, Green M (2004) UASB reactor for domestic wastewater treatment at low temperatures: a comparison between a classical UASB and hybrid UASB-filter reactor. *Water Sci Technol* 49:295–301
- Lin L, Hongbing L, Gu H, Ping L, Jingxian L, Sheng H, Fuxiang W, Rui X, Xiaoxue H (2009) Total pollution effect of urban surface runoff. *J Environ Sci* 21:1186–1193
- Liu Y, Tay J (2002) The essential role of hydrodynamic shear force in the formation of biofilm and granular sludge. *Water Res* 36:1653–1665
- Liu Y, Hai-Lou X, Shu-Fang Y, Joo-Hwa T (2003) Mechanisms and models for anaerobic granulation in upflow anaerobic sludge blanket reactor. *Water Res* 37:61–673
- Lorby J, Flandrios J, Carret G, Pave A (1992) Monod's bacterial growth model revisited. *Bull Math Biol* 54:117–122
- Luo H, Al-Dahhan M (2011) Verification and validation of CFD simulations for local flow dynamics in a draft tube air lift bioreactor. *Chem Eng Sci* 66:907–923
- MacLeod F, Guiot S, Costerton J (1990) Layered structure of bacterial aggregates produced in an upflow anaerobic sludge bed and filter reactor. *Appl Environ Microbiol* 56:1598–1607
- Mahmoud N, Zeeman G, Gijzen H, Lettinga G (2003) Anaerobic sewage treatment in a one-stage UASB and a combined UASB-digester system. In *proc of the seventh international water technology conference, Egypt* 28–30
- Massé D, Masse L (2000) Treatment of slaughterhouse wastewater in anaerobic sequencing batch reactors. *Can Agric Eng* 42:131–137
- McHugh S, O'Reilly C, Mahony T, Colleran E, O'Flaherty V (2003) Anaerobic granular sludge bioreactor technology. *Rev Environ Sci Bio/Technol* 2:225–245
- Nacheva M, Reyes M, Serrano L (2011) Treatment of slaughterhouse wastewater in upflow anaerobic sludge blanket reactor. *Water Sci Technol* 63:877–884
- Namoli S, Mehrotra I (1997) Sludge blanket of UASB reactor: mathematical simulation. *Water Res* 31:715–726
- Ng H, Wong S, Wong S, Krishnan K, Tiew S, Kwok W, Ooi K, Wah Y, Ong S (2006) Integrated anaerobic and aerobic processes for treatment of municipal wastewater. *Water Environ Found* 3205–3216
- Palms S, Loewenthal R, Dold P, Marais G (1987) Hypothesis for pelletisation in upflow anaerobic sludge blanket reactor. *Water SA* 13:69–80
- Pereboom J (1994) Size distribution model for methanogenic granules from full scale UASB and IC reactors. *Water Sci Technol* 30:211–221
- Pereboom J, Vereijken T (1994) Methanogenic granule development in full scale internal recirculation reactors. *Water Sci Technol* 30:9–21
- Richardson J, Peacock D (1994) *Chemical engineering: chemical & biochemical reactors & process control*. Pergamon, Great Britain
- Rodríguez-Gómez R (2011) Upflow anaerobic sludge blanket reactor: modelling. Dissertation, Royal Institute of Technology
- Rodríguez-Gómez R, Moreno L, Liu L (2013) A model to predict the behavior of UASB reactors. *Int J Environ Res* 7:605–614
- Saravanathamizhan R, Balasubramanian N, Srinivasakannan C (2010) Comparison of tanks-in-series and axial dispersion models for an electrochemical reactor. *J Model Simul Syst* 1:171–175
- Seghezzo L (2004) Anaerobic treatment of domestic wastewater in subtropical regions. Dissertation, Wageningen University
- Seghezzo L, Gutierrez M, Trupiano A, Figueroa M, Cuevas C, Zeeman G, Lettinga G (2002) The effect of sludge discharge and upflow velocity on the removal of suspended solids in a UASB reactor treating settled sewage as moderate temperatures: In the VII Latin-American workshop and seminar on anaerobic digestion *Proc Mexico* 367–372
- Sponza D, Isik M (2005) Substrate removal kinetics in an upflow anaerobic sudge blanket reactor decolorizing simulated textile wastewater. *Process Biochem* 40:1189–1198

- Sponza D, Uluköy A (2008) Kinetic of carbonaceous substrate in an upflow anaerobic sludge blanket (UASB) reactor treating 2,4 dichlorophenol (2,4 DCP). *J Environ Manag* 86:121–131
- Tay J, Xu H, Teo K (2000) Molecular mechanism of granulation I: H₂ + translocation — dehydration theory. *J Environ Eng* 126:403–410
- Tiwari M, Guha S, Harendranath C, Tripathi S (2006) Influence of extrinsic factors on granulation in UASB reactor. *Appl Microbiol Biotechnol* 71:145–154
- Vammen K, Hurtado I, Picado F, Flores Y, Calderón H, Delgado V, Flores S, Caballero Y, Jiménez M, Sáenz R (2012) Recursos hídricos en Nicaragua: una visión estratégica. Diagnóstico del agua en las américas. FCCyT, Mexico
- Wang J, Li J, Luan Z, Deng Y, Chen L (2011) Evaluation of performance and microbial community in a two-stage UASB reactor pretreating acrylic fiber manufacturing wastewater. *Bioresour Technol* 102:5709–5716
- Wu M, Hickey R (1997) Dynamic model for UASB reactor including reactor hydraulic, reaction, and diffusion. *J Environ Eng* 123:244–252
- Yetilmezsoy K (2012) Integration of kinetic modeling and desirability function approach for multi-objective optimization of UASB reactor treating poultry manure wastewater. *Bioresour Technol* 118:89–101
- Zhou W, Imai T, Ukita M, Sekine M, Higuchi T (2006) Triggering forces for anaerobic granulation in UASB reactors. *Process Biochem* 41:36–43