11th International Symposium on
Computer Applications in Biotechnology
Leuven, Belgium, July 7-9, 2010

Modeling of the anaerobic digestion of sewage sludge: Evaluation of several reactor configurations

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Abstract: Sewage sludge is usually degraded by means of anaerobic digestion in order to produce biogas and stabilized sludge. Several reactor configurations have been implemented or studied intending to optimize the process; however, there is a lack of reliable mathematical models that can be used for this purpose. This paper deals with that issue by using a simplified model for the anaerobic treatment of sewage sludge. The performance of a conventional continuous digester was compared with a plug-flow reactor and the influence of the recycle ratio, a two-phase system and the reactor size effect and the influence of the temperature in a thermophilic-mesophilic operation were evaluated.

Keywords: Modeling and Identification; Environmental Processes; Wastewater, Bioremediation; Parameter and State Estimation.

1. INTRODUCTION

Anaerobic digestion is a consolidated technology used mainly in the treatment of organic solid waste. Among them, one of the most important applications has been in the anaerobic treatment and stabilization of waste-activated sludge (WAS), generated from the surplus of biomass produced in the aeration tank in activated sludge systems. Continuous or semi-continuous reactors have been implemented for WAS treatment, generally assuming a continuous stirred tank reactor (CSTR) behavior. The organic matter reduction in these reactors (measured as volatile solid, VS) usually is around 50% with a retention time between 20-30 days. The increasing amount of WAS, generated in the wastewater treatment plant is related to the growing population, which has undergone treatment. This has put pressure over the current treatment running system. In order to deal with this challenge, the optimization and enhancement in the performance of the anaerobic reactors that are currently working, as well as, in the design of new facilities, is crucial.

It is clear that a plug-flow reactor (PF) or a system with a large quantity of CSTR reactor connected in series (which behaves, approximately, as PF), might achieve a better removal efficiency and biogas productivity than a one stage reactor (conventional CSTR), as long as the rate of reaction rises with the substrate concentration (increasing function such as first order, Monod, etc) (Levenspiel 1998). However, anaerobic digestion is a complex biological process, with several reactions and populations involved, where several kinetic of growth and inhibitions are present, thus that statement which compares a plug-flow with a CSTR reactor becomes not quite that simple.

Mathematical models play a relevant role in the optimization process, allowing: increasing the knowledge of the process, helping out the formulating and the verification of new hypothesizes and to predict the system response facing different operational or environmental conditions, minimizing the pilot and experimental work. Anaerobic digestion model nº1 (ADM1) (Batstone et al. 2002) reflects the complexity of the anaerobic process; however its high number of parameters makes the parameter identification a tough task and also its application for control purposes. In this sense, several simplified models have been developed, most of them based on three or two reactions (Haag et al, 2003, Bernard et al, 2001).

Some modeling application about PF have been carried out in UASB reactor in anaerobic wastewater treatment (Batstone et al. 2005; Singhal et al. 1998). In the case of anaerobic treatment of solid waste there are some studies with simple approaches (Sans et al. 1994), and also using more complex ones, which take into account: diffusion, convection, and reaction rates in 1-D or 2-D problems treating organic municipal solid waste (OMSW) (Vavilin et al. 2006; Vavilin and Angelidaki 2005). However, there are no studies comparing several configurations of anaerobic reactors in the anaerobic treatment of sewage sludge.

The aim of this study was to compare the performance of several configurations of anaerobic systems treating sewage sludge: PF, two-phase and thermophilic/mesophilic operation. The comparison was done by using simulations with simplified models of the anaerobic digestion processes that considered the main reactions of the process.

2. MATHEMATICAL MODEL

2.1 Model description

A two-population model with hydrolysis and methanogenic as the reactions considered was used in the modeling application. This model was developed by Vavilin and Angelidaki (2005) and modified in Vavilin et al. (2006).

 10.3182/20100707-3-BE-2012.0054

Contois and Monod kinetics were used for hydrolysis and methanogenic reactions, respectively (equations 1 and 2). Non-competitive inhibition by volatile fatty acids (VFAs) for both reactions was considered. Figure 1 shows the bio-reaction pathways used in the modeling application.

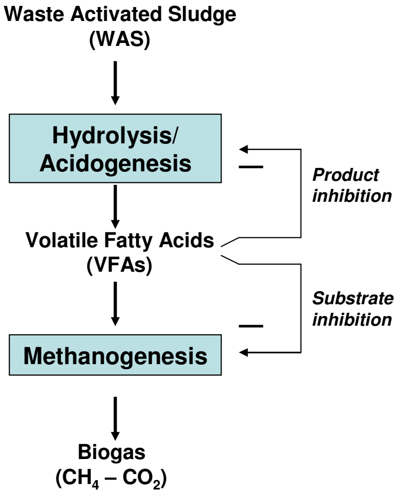

Fig. 1. Model scheme used to simulate anaerobic degradation of WAS (adapted from Vavilin and Angelidaki (2005))

For each reaction the next kinetic were considered:

$$r_H = \mu_{mH} \cdot X_1 \cdot \frac{X_0 / X_1}{K_X + X_0 / X_1} \cdot \frac{K_{IH}}{K_{IH} + S} \qquad (1)$$

$$r_M = \mu_{mM} \cdot X_2 \cdot \frac{S}{K_s + S} \cdot \frac{K_{IM}}{K_{IM} + S} \qquad (2)$$

Where: r_H, hydrolysis reaction rate, r_M methanogenesis reaction rate, X_0, particulate organic matter concentration, X_1 hydrolytic/acidogenic biomass concentration, S volatile fatty acid (VFA) concentration, μ_{mH} maximum specific growth rate of hydrolytic/acidogenic biomass, μ_{mM} maximum specific growth rate of methanogenic biomass, K_X saturation constant of the hydrolysis process, K_{IH} inhibition constant of the hydrolysis process, K_S affinity constant of methanogenic biomass and K_{IM} inhibition constant of methanogenic biomass.

In each CSTR the following set of differential equations were used:

$$\frac{dX_1}{dt} = D(X_{1i} - X_1) + K_1 \cdot (r_H - k_d \cdot X_1) \qquad (3)$$

$$\frac{dX_2}{dt} = D(X_{2i} - X_2) + K_2 \cdot (r_M - k_d \cdot X_1) \qquad (4)$$

$$\frac{dX_0}{dt} = D(X_{0i} - X_0) - r_H \qquad (5)$$

$$\frac{dS}{dt} = D(S_i - S) + K_3 \cdot (1 - K_1) \cdot r_H - r_M \qquad (6)$$

$$q_{CH_4} = A \cdot (1 - K_2) \cdot r_M \qquad (7)$$

Where: K_1 hydrolytic/acidogenic biomass yield, K_2 methanogenic biomass yield, X_2 methanogenic biomass concentration, and A mass fraction of methane in biogas (methane and carbon dioxide): 16/60.

2.2 Model implementation and simulation conditions

This model was implemented in Matlab7.0® and the toolbox *ode45* was used to solve the differential equation systems. In order to compare all systems the same influent characteristics were used. According to reported information, an average value for the VS concentration in waste-activated sludge that is going to be treated by an anaerobic digester, is between 20 and 30 g/L and the typical working organic load rate (OLR) is within 0.8-1.0 kgVS/m^3·d (Zupancic et al. 2008; Shang et al. 2005; Bolzonella et al. 2002). Then, a total volume of each system of 5000 L, a feeding flow of 250 L/d and a concentration of 25 g/L of VS were chosen. Neither VFAs nor biomass were included in the feeding. The performance comparison of the systems was done when steady state conditions were reached. The yield coefficients and the mass fraction of methane in biogas were taken from (Vavilin et al. 2006). The initial condition chosen for X_1 and X_2 were 10 g/L and 5 g/L, respectively.

2.3 Kinetic parameters

There are many studies that have determined kinetic parameters values of an anaerobic digestion process; likewise a wide range of values for these parameters has been reported. For a proper kinetic parameter values choice, it is crucial, at least, to take into account the same substrate that will be used in the simulation. Table 1 presents the kinetic parameters values of WAS anaerobic digestion reported, lately, for hydrolysis and methanogenic reactions.

For mesophilic anaerobic digestion, the following set of kinetic parameters was used: μ_{mH}, 6.8 (d^{-1}), K_X 10.8 g/L (Contois kinetic). The inhibition constant for the hydrolysis by VFA of 15 g/L was taken from (Vavilin et al. 2006), which was used for OMFSW degradation. The decay coefficient was 0.041 d^{-1} value taken from (Sötemann et al. 2005b). The parameters used for Monod kinetic were: μ_{mH} 1.19 d^{-1} and K_s 0.021 g/L. These values are the average values for acetate and hydrogen utilizers. The inhibition constant, Ki 1.5 g/L and a decay coefficient, k_d, of 0.175 d^{-1}, which is the average between the decay, k_d, for acetate and hydrogen utilizers (Table 1).

3. SIMULATION RESULTS AND DISSCUSSION

3.1 PF and CSTR: recycle influence(R)

Figure 2 shows the dynamic behavior of a conventional CSTR system during 200 days of simulation at 20 and 16 d of

HRT. Between 20 and 17 d a similar behavior for all variables is obtained. At an HRT of 17 d (data no shown), a methane flow of 1.9 m^3/d and an effluent COD of 6.4 g/L (81.9% of removal) are obtained. This value of COD removal is particularly high compared with real values obtained in an anaerobic digester. However, it has to be taken into account that the model does not consider the inert part of the organic matter, which may become a significant part of the organic matter entering into to the system. At 16 d, methanogenic biomass washed out from the reactor, thus, under those conditions the reactor behaves as an acidogenic reactor. This behavior is related to the initial biomass concentration, the HRT and, especially, the kinetic of the anaerobic microorganisms. The biomass growth and the biomass washout from the reactor are functions of the biomass concentration. At the beginning, a sharp biomass drop is observed due to the high initial biomass concentration. After that, both terms reach to more or less the same level, but the biomass washout is still a little bit higher than the growth term. Hence, the VFA concentration always increases slightly and reaches the inhibition level, which triggers the final biomass washout of the biomass. This behavior occurs at 16 d, since at lower HRTs, a more continuous biomass washout is observed.

Table 1. Hydrolysis and methanogenic kinetic parameters for anaerobic degradation of WAS

Hydrolysis (Contois function)		
***k_C* (d^{-1})**	***Kx* ($gCOD/gCOD_B$)**	**Reference**
0.2	1.5	(Tomei et al. 2008)
6.797	10.829	(Sötemann et al. 2005b)
5.2	7.9	(Sötemann et al. 2005a)
Methanogenesis (Monod Kinetic and non-competitive inhibition)		
μ_m (d^{-1})	***Ks* (g/L)**	**Reference**
2.08[2]	11.24	(Sosnowski et al. 2008)
9[2b]	0.15[b], 0.2[c], 7e-6[d]	(Blumensaat and Keller 2005)
0.37 [b,5] 1.47 [b,6] 2.0 [d,5] 8.0 [d,6]	0.04 [b,5] 0.3 [b,6] 0.001 [d,5] 0.005 [d,6]	(Siegrist et al. 2002)
4.39[b] 1.2[d]	1.3e-5[b7] 1.56e-4[d7]	(Sötemann et al. 2005b)
***k_d*(d^{-1})**	***Ki* (g/L)**	
0.05 [b,5] 0.2 [b,6] 0.3 [d,5] 1.2 [d,6]	1.5	(Siegrist et al. 2002)
0.037[b] 0.01[d]	-	(Sötemann et al. 2005b)

[2] Maximum specific utilization of VFA rate (kgCOD/kgCOD_X/d), [b]Acetate [c] propionate [d] hydrogen utilizers, [5] Mesophilic,[6] Termophilic [7]mol/L [8]mol organism/mol substrate

The simulation of the behavior of a 10-CSTR system (nearly PF operation) at different recycle ratios is shown in Figure 3. Each curve represents the operation of a 10-CSTR system at different recirculation ratios. All the reactors that make up each system are represented on axis-X, from reactor 1 to reactor 10, i.e. more or less the length of one plug-flow reactor. Axis-Y values represent the steady states that were reached for each recirculation ratio. In order to compare these results with the conventional CSTR, 17 d of HRT was chosen. Without recycle (R=0) the trivial steady state was obtained, washing out the methanogenic biomass due to the VFA accumulation above 20 g/L. The COD removal was negligible. This situation is due to the low HRT in each reactor, despite the fact that the total HRT of the system is equal to the other systems. In these two systems the biomass washout occurred consecutively in each CSTR reactor because the methanogenic biomass decreased its concentration and the acetic acid concentration rose to inhibition levels for the next reactor. Similar results, regarding methanogenic biomass and methane, are obtained for R equal 5 and 10. However, acidogenic biomass, *Xo* and *S* reach similar values in each reactor unlike the sharp profile observed without recycle. This situation is due to these recycle ratios enabling high concentration of acidogenic biomass in the first reactors, increasing the particulate degradation and, consequently, VFA production.

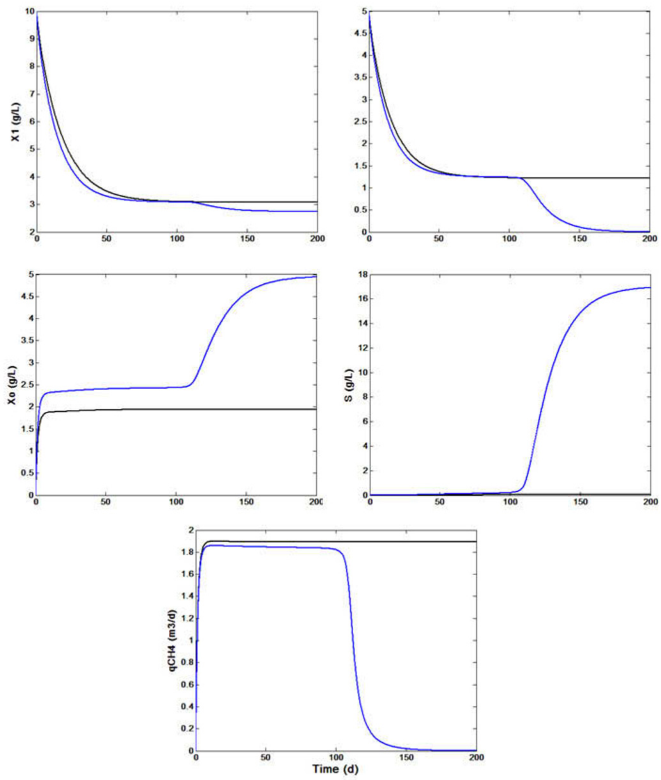

Fig. 2. Simulation of 1-CSTR behavior treating sewage sludge by anaerobic digestion at 20 d (black line) and 16 d (blue line) of HRT.

A recycle ratio of 12 is the minimum required to reach a non-trivial steady state. As similar results are obtained for a ratio of 15 (only slight differences in the profiles are observed) the results obtained with a ratio of 12 were used to compare conventional operations. By choosing the optimum recirculation ratio one could avoid energy and investment cost losses by overestimating pumping needs and prevent system failures by biomass washout or VFA accumulation.

The performance obtained at recycle ratio of 12 was better than that obtained with the CSTR system, the total biogas produced is 2.9 m^3/d (as the sum of the produced one from each reactor), which is 53.7% greater the obtained with the conventional system at the same HRT. Moreover, it can be noted that most of the outlet COD corresponds to the anaerobic biomass developed, which could benefit the down-stream separation process and enhance the post-treatment biological treatment.

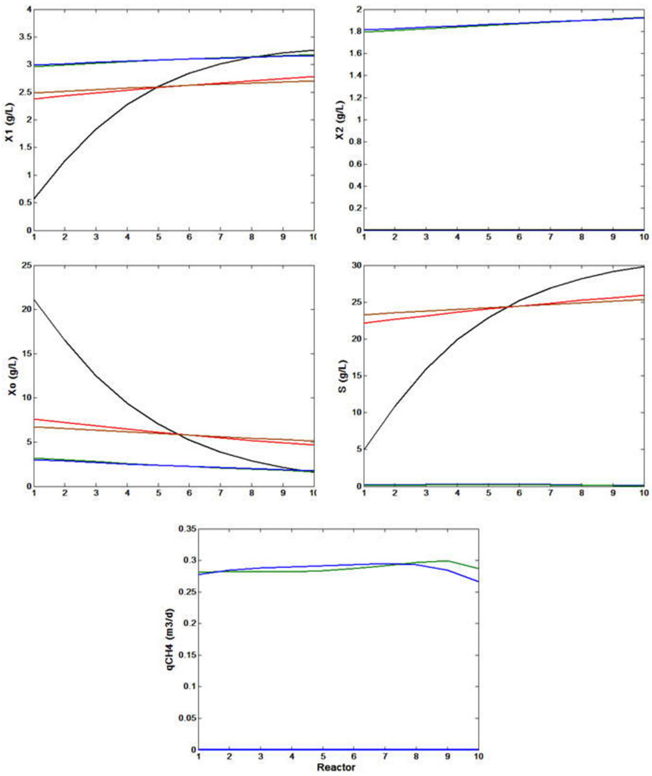

Fig. 3. Simulation of 10-CSTR connected in series treating sewage sludge by anaerobic digestion. Recycle ratio (R): 0 (black line), 5 (red line), 10 (brown line), 12 (green line) and 15 (blue line).

3.2 Two-phase operation. HRT significance

Several two-phase anaerobic systems have been implemented for anaerobic treatment of waste activated sludge in order to separate the two main populations, acidogens and methanogens. Figure 4 shows the performance simulation of the reactors at different HRTs. This parameter was modified changing size of the reactors, but keeping constant the total HRT of the system in 20 d. In the range of HRT analyzed the methanogenic biomass is washed-out from the first reactor, hence biogas production is only obtained at the beginning of the operation. In general, a slight decreasing tendency of the acidogenic biomass concentration is obtained as the HRT decreased, however, a noticeable low concentration is observed at 1 d of HRT, which means that that retention time does not allow the growth of the acidogenic population. According to this, similar behavior is observed for *Xo* y *S*, where a high particulate organic removal and acetic acid production are obtained at highest HRTs. In the case of the second reactor, the acidogenic biomass shows the same profile, reaching a steady state in all HRTs. This means that the hydrolysis of particulate organic matter and acetic acid production will keep occurring in the second reactor. The methanogenic population reached a steady state at HRT of 17, 18 and 19 d (and consequently a constant biogas production), this means that at least a ratio of 3:17 in reactor sizes is necessary to avoid the inhibitory effect of the VFA and to allow the growth of methanogens. The highest COD removal and biogas production is obtained with 3 and 17 d of HRT for reactor 1 and 2, respectively, with 5.28 g/L of COD in the effluent (85% of removal) and 1.93 m^3/d of methane.

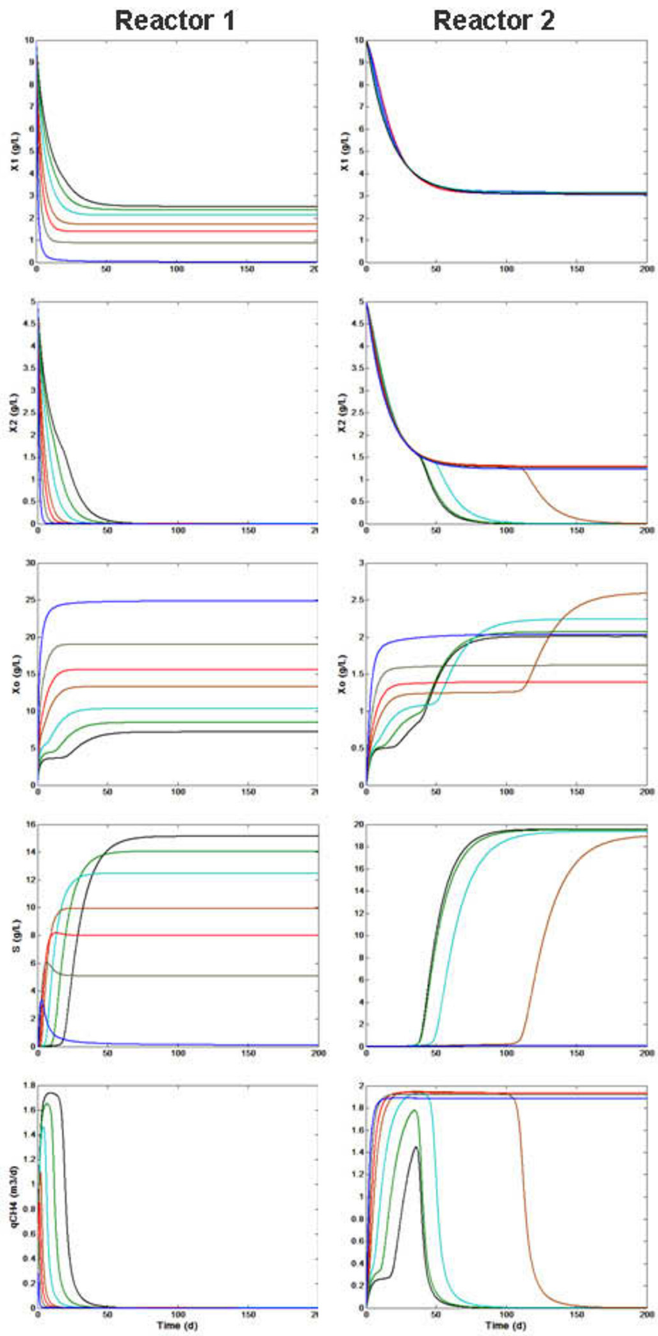

Fig. 4. Performance of a two-phase system at different HRTs. Black line 10/10 d, green line 8/12 d, turquoise blue 6/14 d, brown line 4/16 d, red line 3/17 d, grey line 2/18 d and blue line 1/19.

3.3 Two-phase operation. Temperature effect

Thermophilic conditions, mostly in the first stage of a two-phase anaerobic system, has been used in anaerobic WAS treatment. Reaction rates increase achieving better results than in a single reactor, showing benefits in regards to biogas production, volatile solid reduction and pathogens elimination (Bolzonella et al. 2007; Watts et al. 2006; Song et al. 2004; Jolis et al. 2002).

To simulate the operation of thermophilic/mesophilic system different kinetic parameters were used. For methanogenic biomass, μ_{mM}, K_S and k_d, were estimated as the average of reported values by Siegrist et al. (2002) in thermophilic conditions, of acetoclastic and hydrgenotrophic population. There are no reported values for Contois coefficients in thermophilic conditions, thus the μ_{mH} was estimated according to the increase of 60% obtained by Siegrist et al. (2002) in the first order coefficient comparing mesophilic and thermophilic conditions. Hence, the μ_{mH} value was estimate in 10.9 d^{-1}. As well as the maximum specific growth rate increases with the temperature, the decay coefficients so do. Hence the values used were (from Table 1): kd_1=1.69 d^{-1} and kd_2=0.7 d^{-1}. The value for Kx was maintained due to this parameter has not shown significant changes with the temperature (Donoso-Bravo et al. 2009). Also the value of the inhibitions constants were maintained constant.

The results of the thermophilic/mesophilic simulation are shown in Figure 5. The first difference with the previous process is that the two-phase system reaches a steady state at HRTs of 10/10 d, due to both populations can coexist in the first reactor. In this condition, the COD of the effluent from the thermophilic reactor is of 5.6 g/L equivalent to 84% of removal. The outlet COD of the system (mesophilic reactor) is 2.16 g/L, which means the second reactor was able to remove 61% of the COD, thus the COD removal of the system reached 94%. It can be noted, that the mesophilic reactor does a kind of pos-treatment of the effluent. The biogas production is 1.81 and 0.21 m^3/d in each reactor, which represents a 5% increase compared with the two-phase mesophilic system. In order to evaluate the effect of the HRT reduction in the thermophilic reactor, the volume of the reactor was diminished, but the HRT of the mesophilic one was maintained constant. Figure 5 shows that the HRT of the thermophilic reactor could be reduced up to 7 d, without significant changes in the performance of the system, which would imply a reduction in the investment and operational costs, since a smaller reactor and less energy for heating would be needed. By contrast a HRT of 6 d produces a washout of the methanogenic biomass and, with that, an overall system failure due to VFA accumulation. On the other hand, the volume of the mesophilic reactor might be reduced depending of the requirements of biogas or the effluent quality. For instance, with a HRT of 7 d, the biogas produced is almost the same as with the two-phase mesophilic system, but uses 30% less volume of the total system.

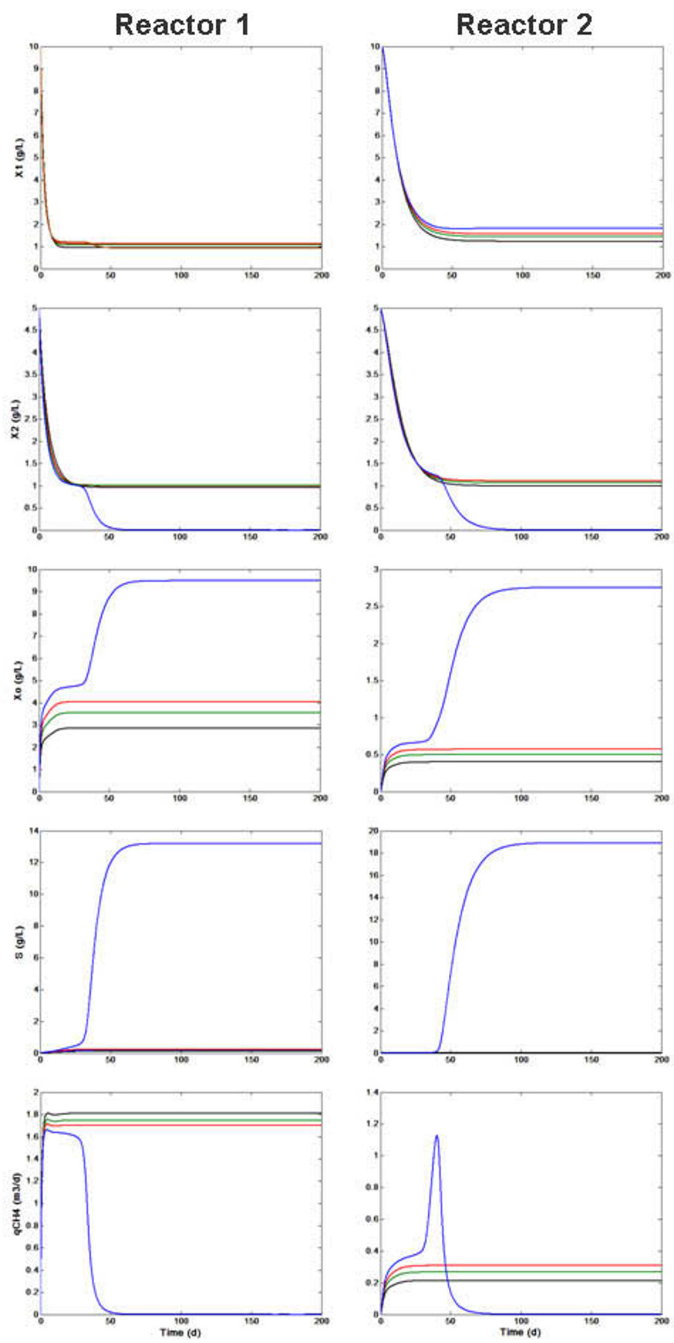

Fig. 5. Performance of a two-phase system, thermophilic and mesophilic reactor at different HRTs. Black line 10/10 d, green line 8/10 d, red line 7/10 d and blue line 6/10 d.

6. CONCLUSIONS

This simulation allows us to know that there are several combinations regarding operational conditions, where a stable system behavior can be achieved. Therefore with a reliable and validated model, as well as, proper kinetic parameters, is possible to optimize the process, maximizing the interest variables. As previously mentioned, the results obtained are strongly dependent on the kinetic parameters, for instance, higher values for the maximum specific growth or for the inhibition constant of the methanogenic biomass may mean that biomass washout will not occur at certain input conditions. In any case, these results illustrate the characteristic of the process and its complexity which are important factors in the determination of the optimal reactor configuration.

ACKNOWLEDGEMENTS

This research group is "Grupo de excelencia GR76 de la Junta de Castilla y Leon" and member of the Consolider_Novedar framework (Programa Ingenio 2010, Ministerio de educacion y Ciencia)

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