Municipal Sludge Degradation Kinetic in Thermophilic CSTR

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The performance of a pilot-scale continuous-flow stirred-tank reactor (CSTR) treating municipal sludge under thermophilic conditions has been studied. Two pilot-scale reactors (CSTR1 (175 L) and CSTR2 (850 L)) were operated at different hydraulic residence times (θ: 40 to 15 days). The anaerobic sludge processes are generally affected by variations in the concentration of substrate (determined as influent volatile solids, VS) and volumetric flow, both of which lead to a modification in biomass concentration and VS removal efficiency. This unsteady-state situation is mathematically explained in terms of an autocatalytic kinetic model. The general kinetic equation in this model has been applied to experimental data obtained in CSTR1. The fit of the experimental data to the model was used to estimate kinetic parameters and the yield coefficients (μ_{max}, α, $Y_{P/S}$). The estimated parameters were μ_{max}: 0.175d^{-1}, α: 0.358, $Y_{P/S}$: 0.309 m^{3}CH$_4$/kgVS). These parameters were subsequently used to model the substrate utilization rate and the methane generation rate in CSTR2. The model with the estimated parameters was found to provide excellent results, and is satisfactory in describing the concentration of VS and the methane generation rate in an actual digestion plant. © 2006 American Institute of Chemical Engineers *AIChE J,* 52: 4200–4206, 2006

Keywords: anaerobic sludge, kinetic model, hydraulic retention time, unsteady state

Introduction

Anaerobic digestion is one of the most widely used processes for the stabilization of wastewater treatment plant sludge. The widespread use of this approach over and above other stabilization processes stems from its potential advantages in comparison to other processes. A high number of processes have been reported for the upgrading of sludge digestion, with thermophilic anaerobic digestion (55 °C) being an alternative to mesophilic anaerobic digestion (35 °C)[1,2,3,4]

Volatile solids (VS) content in a reactor is used as an indicator of the amount of organic matter contained in sludge. Hence, the amount of VS destruction achieved in a sludge stabilization process can be used to measure the effectiveness of the process. The VS reduction achieved depends on the type of sludge digested (primary, waste activated or a mixture of these sludges), temperature and hydraulic residence time (HRT).

It is well known that the hydraulic-residence time of a digester is one of the most important factors for the control of anaerobic digestion systems. Although a tremendous amount of research has focused on the effect of HRT in anaerobic systems, sufficient information is still not available to clarify the effect of HRT on thermophilic reactor performance.[5,6,7,8,9] Anaerobic sludge processes are also affected by the variation of influent VS concentration. Both, influent VS concentration and volumetric flow (hydraulic residence time, θ) are related by the organic loading rate parameter (OLR = S_0/θ).

The chemical engineering literature contains numerous useful models that have been formulated for the description of biological processes under steady-state conditions. Some of these models are general kinetic models for bacterial growth

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(Tessier, Monod, Moser, Contois (as it appears in Bailey and Ollis)),[10] others are mathematical models formulated specifically for anaerobic processes (Chen and Hashimoto[11]; Bolte and Hill[12]; Alatiqi et al.[13]), and the last ones are dynamic multivariable models (Angelidaki et al.[14]; Siegrist et al.[15]; Anaerobic Digestion Model No. 1 (ADM1) developed by the International Water Association (IWA) task group for mathematical modeling of anaerobic processes (Batstone et al.[16]). All of these mathematical models use kinetic expressions that depend on effluent substrate mass concentration. This variable reflects volatile solids (VS), or the chemical oxygen demand (COD) concentration to which micro-organisms are exposed in the completely mixed reactor.

However, steady-state conditions are not often achieved in anaerobic digestion sludge processes, because most plants are subject to disturbances when working under steady-state conditions. In these circumstances, a kinetic model based on steady-state conditions would not accurately reflect the effects of process disturbances and would be of little use for simulation studies on plant dynamics and control systems. Conditions that could lead to an unsteady state situation in an anaerobic sludge process include the variation of influent COD or VS concentration (S_0), and the volumetric flow (θ).

Kinetic model proposed

Romero[17] proposed an autocatalytic kinetic model to describe the performance of degradation processes under different experimental conditions, including nonstationary states. The development of the model has been reported in detail in previous articles[18,19] of the authors. The model has been successfully applied to different digester configurations under different operational conditions.

The mathematical expression of the general kinetic model to describe the substrate utilization rate as a function of the substrate concentration is

$$(-r_S) = \left(-\frac{\mathrm{d}S}{\mathrm{d}t}\right) = \mu_{\max}\left(\frac{(S_0 - S)(S - S_{\mathrm{NB}})}{S_0 - S_{\mathrm{NB}}}\right) \tag{1}$$

where

$(-r_S)$ is the net substrate consumption rate ($\mathrm{ML}^{-3}\ \mathrm{t}^{-1}$)

S is the effluent substrate mass concentration (ML^{-3})

S_0 is the initial influent substrate concentration (ML^{-3})

S_{NB} is the nonbiodegradable substrate concentration (ML^{-3})

$\mu_{\max}$ is the maximum specific growth rate of micro-organisms (t^{-1})

t is time t

The Romero kinetic model for wastewater treatment processes was developed by considering the autocatalytic character of the microbiological reactions involved. The main characteristics of the proposed model are its general applicability and its flexibility. The expression obtained for the substrate consumption rate is a second-order polynomial with respect to the substrate concentration remaining in the bulk liquid. As a consequence, a plot of substrate consumption rate vs. substrate concentration gives a parabolic function from which the kinetic parameters can be obtained. The expression for the substrate concentration vs. the incubation time for discontinuous processes can be obtained by integration of the model equations by numerical methods.[18]

Model of substrate consumption

In order to obtain the design expression of mathematical model, the digester is modeled as a continuous-flow stirred-tank reactor (CSTR). The mass balance equation is as follows

$$\begin{aligned} V\frac{\mathrm{d}S}{\mathrm{d}t} &= Q \cdot S_0 - Q \cdot S - (-r_S) \cdot V \\ \frac{\mathrm{d}S}{\mathrm{d}t} &= \frac{(S_0 - S)}{\theta} - (-r_S) \end{aligned} \tag{2}$$

V is the digester volume (L^3); Q is the feed-flow in and out of the digester (Lt^{-1}); S_0 and S are total substrate concentrations in the digester influent (S_0), and the digester effluent (S), respectively, (ML^{-3}); $(-r_S)$ is the substrate consumption rate (rate of biodegradation, $\mathrm{ML}^{-3}\ \mathrm{t}^{-1}$), and θ is the substrate residence time (t).

S_0 and θ are prefixed variables that allow the substrate consumption rate $(-r_S)$ to be calculated from the experimental results obtained (experimental values of substrate, S).

When the digester is operating over a long period of time, we assume that pseudo-stationary conditions are achieved if the control parameters of the anaerobic process (%VS removal and biogas production and composition) are maintained at constant values. In this case, the accumulation term in Eq. 2 is negligible, and the previous equation can be modified as follows

$$(-r_S) = \frac{S_0 - S}{\theta} \tag{3}$$

This hypothesis involves the assumption that, even when the feed does not have constant composition in terms of volatile solids (VS) or chemical oxygen demand (COD), the values of effluent sludge organic matter concentrations and methane generation are approximately constant.

Considering the previous general Eq. 1 to describe the substrate utilization rate and accepting Eq. 3, the following equation can be obtained[19]

$$\begin{aligned} S_{\mathrm{EST}} = S_{\mathrm{NB}} + \frac{S_0 - S_{\mathrm{NB}}}{\mu_{\max}\theta} &= \alpha S_0 + \frac{S_0(1-\alpha)}{\mu_{\max}\theta} \\ &= \alpha S_0 + \left(\frac{1-\alpha}{\mu_{\max}}\right)\left(\frac{S_0}{\theta}\right) \end{aligned} \tag{4}$$

where α is a dimensionless parameter that represents the nonbiodegradable substrate fraction in the feed as the ratio S_{NB}/S_0.

For Eq. 4, it is assumed that: (a) Nonbiodegradable substrate by the micro-organisms responsible of the process is proportional to total substrate concentration present in the feed, and (b) The $\mu_{\max}$ parameter represents the maximum specific growth rate of active micro-organisms in the process.

Under *nonstationary conditions*, the accumulation term in Eq. 1 is not negligible. This consideration requires the resolution of a differential equation that must be integrated to obtain the following

$$S(S_0, \theta, t) = \frac{S_0(S_{t=0} - S_{\mathrm{EST}}) + S_{\mathrm{EST}}(S_0 - S_{t=0})e^{(\mu_{\max} 1/\theta)t}}{(S_{t=0} - S_{\mathrm{EST}}) + (S_0 - S_{t=0})e^{(\mu_{\max} 1/theta)t}} \tag{5}$$

where $S_{t=0}$ is the substrate concentration within the system when the experimental conditions are modified (ML^{-3}); S_{EST}

represents the value that the effluent should have under stationary conditions (ML^{-3}), and t is the operation time that has elapsed from the point where the conditions were modified (t).

Hence, the substrate concentration in the effluent S, is a function of kinetic parameters, such as $\mu_{\max}$ and α, and is dependent on operational variables, such as S_0, θ and t.

Model of product generation

Accepting that the product generation rate is a linear function of substrate utilization rate in the CSTR (according to the product-associated model proposed by Gaden[20] and Chynoweth et al.[21,22], the methane production rate can be written as

$$\gamma_{CH_4} = Y_{P/S}\left(\frac{S_0 - S}{\theta}\right) \tag{6}$$

where γ_{CH_4} is the volumetric methane generation flow, expressed as m^3CH_4/m^3digester·day (t^{-1}) and $Y_{P/S}$ represents the yield coefficient of methane generation expressed as the ratio between methane produced to substrate consumed, m^3CH_4/kg organic matter (L^3M^{-1}).

Assuming Eq. 4, the γ_{CH_4} equation developed for stationary conditions can be expressed as

$$\gamma_{CH_4} = Y_{P/S}\left(\frac{S_0 - \left(\alpha S_0 + \frac{S_0(1-\alpha)}{\mu_{\max}\theta}\right)}{\theta}\right) = Y_{P/S}\frac{S_0(1-\alpha)}{\theta}\left(1 - \frac{1}{\mu_{\max}\theta}\right) \tag{7}$$

Similarly, substituting Eq. 5 into Eq. 6, we can obtained the expression to describe the anaerobic process under nonstationary conditions.

Objectives

The aims of the study described here are as follows:

(a) to describe the performance of two pilot-scale continuous-flow stirred-tank reactors treating municipal sludge under thermophilic (55 °C) conditions operating at different hydraulic residence times.

(b) to estimate kinetic parameters, maximum specific growth rates ($\mu_{\max}$), nonbiodegradable substrate fraction (α) and methane yield ($Y_{P/S}$) with Romero's kinetic model[17] under stationary operational conditions.

(c) to validate the Romero model[17] under nonstationary conditions. Hence, the model was provided with estimated parameters and was tested with experimental data from a raw sludge digestion process in a pilot-scale CSTR (850 L).

Materials and Methods

This article describes the use of two pilot-scale bioreactors treated as continuously-flow stirred-tank reactor (CSTRs) for the degradation of municipal sludge at anaerobic thermophilic conditions. A pilot-plant reactor (175 L) is operated under pseudo-stationary conditions, and the results are used to estimate the parameters of Romero kinetic model.[17] These parameters are then used to test the predictive capability of Romero model[17] for a second pilot-plant bioreactor (850 L) operated under nonstationary and continuous feed conditions in the anaerobic thermophilic digestion of municipal sludge.

Experimental reactors

Two pilot-plant digesters were used in this study to treat municipal sludge under anaerobic thermophilic conditions (Figure 1).

CSTR1 pilot digester (175 L). CSTR employed in this study had an operational volume of 0.15 m^3. The temperature was maintained within the thermophilic range (55 ± 2 °C) by recirculation of temperature-controlled water through an internal coil. The reactor was operated under thermophilic conditions for a prolonged period of time.

CSTR2 pilot digester (850 L). The second pilot-plant scale continuously-flow stirred-tank reactor (CSTR) employed in this study had an operational volume of 0.75 m^3 and was made from polyester fiber. The temperature was maintained in the range 55 ± 2 °C by a tubular heat exchanger.

In both reactors, a certain volume of digested sludge (depending on the θ imposed) was withdrawn from the reactor three times per day, and an equal volume of raw sludge was pumped into the recycle line of the digester through a variable speed centrifugal pump in order to provide pseudo-complete mixing conditions in the liquid phase. A recycle flow was also drawn from the bottom of the reactor and pumped to the top of the reactor in order to maintain mixed conditions in the digester.

Both digesters can be considered as continuous-flow stirred-tank reactors (CSTR) on the basis of the high-recirculation rate imposed (50 L/h), and the high-recirculation ratio (recirculation flow/effluent flow), as proposed by Levenspiel[23]. The mixing caused by the generation of biogas in the anaerobic process also contributes to this situation.

Feed solutions

The reactors were fed with prethickened combined primary and secondary waste sludge from the wastewater treatment plant (WWTP) at Jerez de la Frontera, Spain. The raw sludge contained 35 ± 3gVS/L and had a pH of 6.1.

The hydraulic residence time was gradually decreased from θ: 40 to 15 days, and was kept constant during each stage until pseudo-steady state conditions were reached. The attainment of the pseudo-steady state was verified after an initial period by checking whether the constant effluent characteristic values (VS removal and methane generation) were the means of the last measurements in each stage. Three θ for operation at θ values of 27, 20 and 15 days, and one θ for 40 days (due the low-organic loading rate applied).[5,24]

Analytical methods

Daily, parameters measured for influent and effluent samples were as follows: chemical oxygen demand (COD), total solids (TS) and volatile solids (VS), pH and bicarbonate alkalinity (this one only of effluent). These analytical determinations were performed according to "Standard Methods".[25]

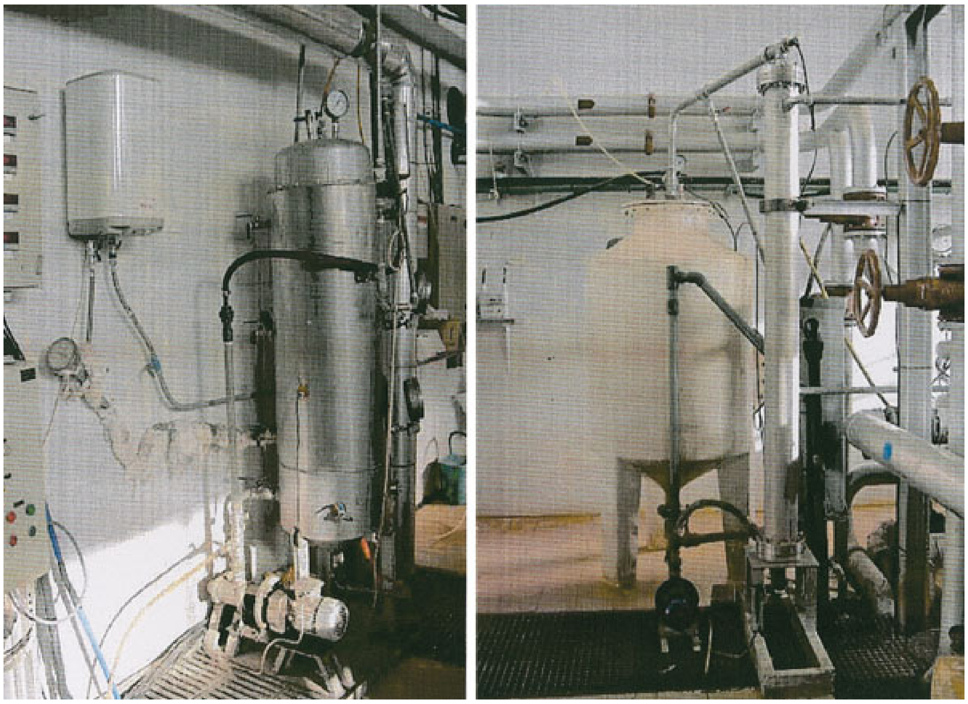

Figure 1. 175 L Pilot-plant digester (CSTR1), and 850 L Pilot-plant digester (CSTR2).

[Color figures can be viewed in the online issue, which is available at www.interscience.wiley.com].

Individual and total volatile fatty acid concentrations (VFA) was determined by gas chromatography according the method described in previous articles.[24]

Daily, gas production and composition of biogas (methane and carbon dioxide percentages) were analyzed. The volume of gas produced in the reactor was measured by a mass flow sensor, whereas gas composition (methane and carbon dioxide) was determined by gas chromatography according the method described in previous articles.[24]

Experimental procedure

Initially, the experimental protocol was defined to examine the effect of increasing the organic loading rate on the efficiency of the CSTR1 and to assess its steady-state performance. This reactor was subjected to a programme of steady-state operation over a range of sludge residence times (θs) of 40, 27, 20 and 15 days and organic loading rates (OLR) in the range 0.96–2.77 kgVS/m^3· d[5].

Experimental data obtained from CSTR1 were used to estimate the kinetic parameters and the yield coefficients ($\mu_{\max}$, S_{NB}, $Y_{P/S}$) of the Romero model[17] on the assumption of pseudo-stationary conditions (Eqs. 4 and 7). These kinetic parameters were used to test the predictive capability of the model for CSTR2 operated under continuously feed conditions using the model developed for nonstationary conditions. The operational conditions studied for CSTR2 were $\theta = 27$, 20 and 15 days, and OLRs in the range 1.48 kgVS/m^3· d and 2.63 kgVS/m^3· d.[24]

Romero kinetic model was used to test the substrate consumption (Eq. 5) and methane generation (Eq. 6) in CSTR2.

Results and Discussion

CSTR1 performance

The progress of the digestion process was determined by monitoring VS removal (VS$_r$), gas production and gas composition, pH and total and individual volatile fatty acids (VFA) levels as described in previous articles.[5,24] COD and volatile solids reduction VS, are commonly used parameters to measure the performance of anaerobic digestion processes. However, COD data are very difficult to measure due the nature of the feed and, in this experimental work, such data were not used as control parameters for the digestion process.

The averaged experimental data obtained from the 175 L reactor under pseudo-steady state conditions at different θ values are summarized in Table1.

It was confirmed experimentally that the thermophilic sludge reactor CSTR1 could achieve $> 57.8\%$ VS reduction at a VS loading rate of 0.96 kgVS/m^3· d in the treatment of raw sludge from a municipal treatment plant under steady-state conditions ($\theta = 40$ days). A higher-degradation efficiency is associated with increased gas production, and an improvement in the energy balance of the process. The greatest efficiency in terms of the methane production rate was 0.31 m^3/m^3· d for an OLR of 2.77 kgVS/m^3· d (0.32 m^{3}CH$_4$/kgVS$_r$) with a θ value of 15 days[5].

CSTR1 Modeling

Equation 3 can be used to describe the kinetic performance of CSTR1. In all equations, biodegradable substrate concentration was evaluated as volatile solids.

Table 1. Experimental Performance Data for CSTR1 (175 L) at Different θ Values

θd	S_0 kg/m^3	S_e kg/m^3	S_r %	OLR kgVS/m^3 · d	ORR kgVS/m^3 · d	CH_4 m^3/m^3 · d	CH_4 m^3/kg S_r
75	39.0 ± 3.0	17.8 ± 2.1	54.4 ± 3.9	0.52 ± 0.05	0.28 ± 0.02	0.10 ± 0.01	0.35 ± 0.07
40	38.4 ± 2.7	16.2 ± 1.8	57.8 ± 4.2	0.96 ± 0.10	0.56 ± 0.09	0.19 ± 0.01	0.37 ± 0.05
27	37.2 ± 1.9	18.1 ± 2.0	51.5 ± 5.0	1.38 ± 0.18	0.71 ± 0.11	0.20 ± 0.01	0.32 ± 0.08
20	39.0 ± 2.3	21.7 ± 1.9	44.4 ± 4.7	1.95 ± 0.22	0.87 ± 0.10	0.22 ± 0.06	0.29 ± 0.06
15	41.5 ± 2.8	23.1 ± 2.2	44.3 ± 4.9	2.77 ± 0.27	1.23 ± 0.12	O.31 ± 0.08	0.32 ± 0.07

The changes of substrate (VS) with θ in the 175 L digester can be fitted by the general kinetic model, Eq. 4. The identification of the kinetic parameter was achieved using nonlinear regression algorithms, Marquardt[26], by fitting the experimental data in Table2. This algorithm estimates values for model parameters by minimizing the sum of the squared differences between the observed and predicted values. Different initial values of the model parameters were tested to ensure that global minima were obtained rather than local minima.

Estimated kinetic constants according to the substrate consumption model (nonlinear regression) are α: 0.358 ± 0.052, μ_{max}: 0.196 ± 0.013, r^2: 0.91.

The correlation indexes are high (0.91), indicating the goodness of the adjustment obtained. The physical and microbiological significance kinetic parameters enable to compare their values with the experimental results:

- the parameter α is 0.358 ± 0.052, that represent the nonbiodegradable substrate fraction in the feed as the ratio S_{NB}/S_0. S_0 is the initial substrate in each essay (as VS). S_{NB} represent the concentration of substrate that could not be used by the anaerobic population at the selected experimental conditions.[5] Hence, the theoretical S_{NB} parameter can be estimated starting from the α parameter. This theoretical value (approximately 14–15 kgVS/m^3, depending of influent VS), is close to the experimental residual substrate (as VS) obtained at the end of each experiment.
- μ_{max} parameter, approximately 0.196 ± 0.013 d^{-1}, is the maximum specific growth rate of the microorganisms implicated in the process. Literature data indicate that, in balanced processes, the value of μ_{max} is representative of the maximum specific growth rate of the methanogenic microorganisms. This fitted value is consistent with that obtained by Siegrist et al.[15] for acetotrophic methanogens in thermophilic anaerobic sewage sludge digestion, as well as the value proposed by Lokshina et al.[27] in the evaluation of kinetic coefficients using integrated Monod and Haldane models.

The data expressed in Table 2 were used in conjunction with a value of $\alpha = 0.358 \pm 0.052$ to obtain the follow kinetic parameters by applying Eq. 7 to fit the methane generation rate by nonlinear regression of the data using the Marquardt algorithm.[26]

The results of the fitting of the experimental methane data obtained are: $Y_{P/S} = 0.309 \pm 0.041$ m^{3}CH$_4$/kg organic matter and μ_{max}: 0.155 ± 0.010 d^{-1}.

The correlation index is 0.94, which indicates the goodness of the fit. All values of the kinetic parameters obtained are consistent with the physical and microbiological significance. Accepting α: 0,358, the yield coefficient of methane generation can be calculated. The value obtained was 0.309 ± 0.041 m^3 of methane produced per kg of substrate (VS) consumed, m^{3}CH$_4$/kg organic matter. This value is in accordance with the published by other authors[2,3] operating at full-scale with municipal sludge at thermophilic conditions.

The μ_{max}: 0.155 ± 0.010 d^{-1}, is closely to the value obtained in the previous fitted of the substrate, corroborating the microbiological significance of the parameter Also, this value is similar to the estimate data proposed by other authors.[15,27]

CSTR2 performance

CSTR2 was subjected to a program of steady-state operation over a range of sludge residence times (θs) of 27, 20 and 15 days. The digester was fed with raw sludge (containing approximately 34.8 g/L volatile solids) three times per day.[24]

Under thermophilic conditions and $\theta = 27$ days, the reactor was operated with an organic loading rate of 1.48 kgVS/m^3· d. The solids removal efficiency of the reactor was found to be 42.9%, while the volumetric methane production rate in the digester reached 0.35 m^3/m^3· d. Over an operating period of 150 days, an OLR of 2.63 kgVS/m^3· d was achieved with 41.8% VS removal efficiency in the pilot sludge digester ($\theta = 15$ d). During this period, the volumetric methane production rate in the digester reached 0.20 m^3/m^3· d and 0.20 m^3/kgVS$_r$.

The greatest efficiency in terms of substrate removal was 54.3% for an OLR of 1.71 kgVS/m^3· d and $\theta = 20$ d. Under these conditions, the generation of biogas and methane were 0.86 and 0.58 m^3/m^3· d, respectively, with a methane yield of 0.70 m^3/kgVS$_r$.

CSTR2 Modeling

Steady-state conditions are not often reached in CSTR2 because the substrate (VS) characteristics and concentration are modified daily. Hence, Eqs. 5 and 6 allow the estimation of

Table 2. Experimental Influent and Effluent Substrate (VS) and Volumetric Methane Production Rate at Different θ Conditions

θ, days	40	27	20	15
VS$_0$ (g/L)	38.44 ± 3.01	37.35 ± 2.41	39.02 ± 3.12	41.48 ± 2.60
VS (g/L)	16.21 ± 1.84	18.12 ± 1.93	21.69 ± 1.72	23.10 ± 2.11
γ_{CH4}(LCH$_4$/L · day)	0.171 ± 0.009	0.217 ± 0.010	0.241 ± 0.010	0.322 ± 0.002

the evolution of the substrate consumption (as volatile solids, VS), and methane generation under nonstationary conditions.

The kinetic parameters obtained from CSTR1 (α, $\mu_{\max}$ and $Y_{P/S}$) can be used to predict the performance of CSTR2 in the anaerobic digestion of sewage sludge.

The estimated parameters used in the modeling of CSTR2 are: α: 0.358 and $Y_{P/S}$: 0.309 $m^3CH_4/kgVS$. For the $\mu_{\max}$ parameter, we can use anyone of the two values obtained in the previous adjustments, but it is prefer to use the medium value of the date obtained by the fitting of the substrate consumption and methane generation, $\mu_{\max}$: 0.175 d^{-1}.

Equation 5 represents the evolution of substrate with time for different hydraulic residence times. Therefore, a knowledge of different kinetic parameters from CSTR1 and the new operating conditions allowed us to estimate S (organic matter concentration in the effluent) at any time during the process.

Equation 6 can be used to predict the evolution of the methane generation rate in CSTR2 for different hydraulic residence times.

The experimental data and estimated evolution curves for substrate concentration (expressed as $kgVS/m^3$digester) and methane generation rate ($m^3/m^3 \cdot d$) vs. time (days) are shown in Figures 2, 3 and 4, for the different hydraulic residence times tested.

As can be seen, the model can adjust the experimental evolution of substrate (VS) in the thermophilic sludge digestion process under nonstationary conditions. However, the methane generation was underestimated due to the partial inhibition detected in the methanogenic step in CSTR1, because the accumulation of VFA in the reactor.[4] This affect to the value of the kinetic parameter, $Y_{P/S}$, estimated.

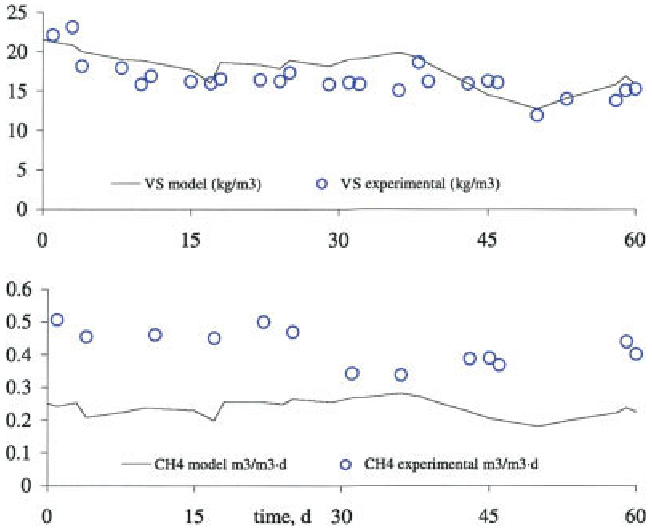

Figure 3. CSTR2 experimental data (o) and predicted values (––) for substrate consumption (VS), and methane generation at 20 days θ.

[Color figures can be viewed in the online issue, which is available at www.interscience.wiley.com].

Conclusions

1. It was confirmed experimentally that continuous-flow stirred-tank technology can support high-loading rates in the treatment of municipal sludge under thermophilic conditions, with high-substrate removal efficiency rates and high-methane generation rates achieved.

2. Romero kinetic model[17] can be used to describe the performance of thermophilic anaerobic continuous-flow stirred-tank reactors with respect to both the substrate utilization, and the product generation under stationary state operating conditions. The values of the kinetic parameters have both physical and microbiological significance ($\mu_{\max}$: 0.175 ± 0.011d^{-1}, α: 0.358 ± 0.052, $Y_{P/S}$: 0.309 ± 0.041 $m^3CH_4/kgVS$).

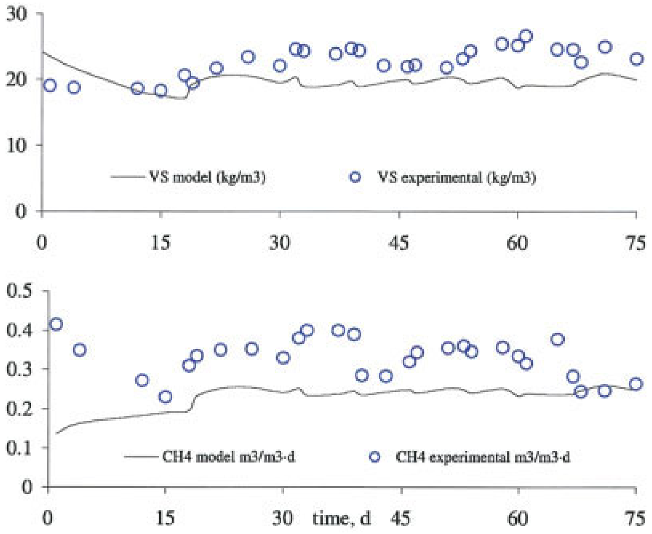

Figure 2. CSTR2 experimental data (o) and predicted values (––) for substrate consumption (VS), and methane generation at 27 days θ.

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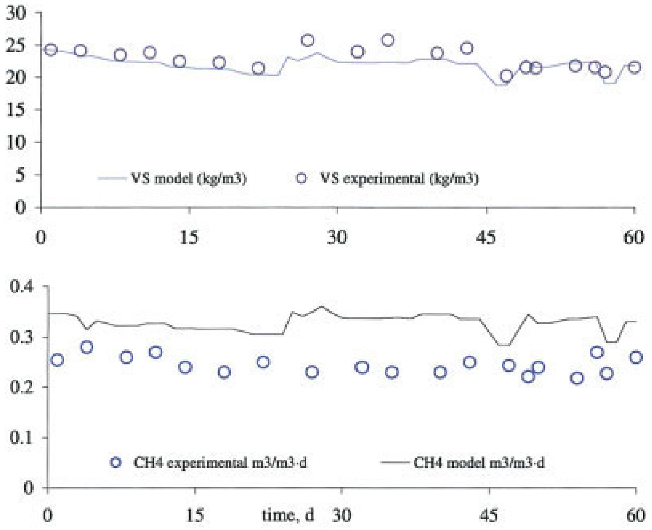

Figure 4. CSTR2 experimental data (o) and predicted values (––) for substrate consumption (VS), and methane generation at 15 days θ.

[Color figures can be viewed in the online issue, which is available at www.interscience.wiley.com].

3. Romero kinetic model[17] is able to predict the substrate utilization and the methane generation under nonstationary state operating conditions at pilot-scale CSTR.

Notation

CSTR = continuous flow stirred-tank reactor.
HRT = hydraulic residence time, t
OLR = initial organic load rate
ORR = organic removal rate
$(-r_S)$ = net rate of substrate consumption, $ML^{-3}t^{-1}$
S_{NB} = nonbiodegradable substrate concentration, ML^{-3}
S_t = total influent substrate concentration, ML^{-3}
$S_{t=0}$ = initial influent substrate concentration, ML^{-3}
t = time, t
VFA = volatile fatty acids, ML^{-3}
VS = volatile solids, ML^{-3}
$Y_{P/S}$ = yield coefficient of methane generation expressed as the ratio between methane produced to substrate consumed, m^3CH_4/kg organic matter (L^3M^{-1})

Greek letters

α = nonbiodegradable substrate fraction in the feed, as the ratio S_{NB}/S_0, adimensional
μ_{max} = maximum specific growth rate of micro-organisms, T^{-1}
θ = hydraulic residence time, t

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