

Modeling and Simulation of Biological Anaerobic Treatment of Sludge Resulted from Wastewater Treatment

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Abstract: The paper presents a kinetic model of anaerobic digestion based on mass balance of substrate, microorganisms and methane production. The model is simulated using a customized Simulink model and the value of maximum specific growth rate of microorganisms is calibrated to fit the theoretical results with experimental ones regarding methane production. The experimental data were obtained during a three months measurements campaign in 2010 at Wastewater Treatment Plant Constanța South, Romania.

Key-Words: - wastewater treatment, anaerobic digestion, modeling, simulation

1 Introduction

Anaerobic fermentation is widely used as sludge handling technology in wastewater treatment plants. In bioreactor the organic substrate is mineralized to methane and carbon dioxide as the result of biochemical reactions performed by distinctive groups of microorganisms growing in the same medium, [7]. The first group consists of optional anaerobic bacteria which, by means of extra-cellular enzymes, convert macro-cellular products into simpler compounds such as alcohol, fatty acids, amino-acids, aldehyde, as well as into important amounts of carbon dioxide and smaller volumes of other gases; this is the acid stage. The acid stage of digestion is fast and less sensitive to environment conditions. The second group of microorganisms - the methane bacteria - is

completely anaerobic and converts the products of the acid stage to methane and carbon dioxide by the action of intracellular enzymes. This is the gasification stage and it is the limited stage of the process because of longer periods of growth of methane bacteria.

The main benefit of the process is the biogas production that can be used to decrease the operational costs of wastewater treatment plant. Modeling anaerobic digestion is very complicated because of the unsteady state behavior and the interaction of different parameters – physical, chemical, biochemical and hydraulical. The kinetics of the digestion process depends on several factors: a) temperature; b) pH level; c) concentration of organic matter expressed in DSS, sludge concentration; d) presence of inhibitors; e) mixing and external circulation; f) detention time; g) organic/mineral ratio;

organic/nutrient ratio, especially nitrogen and phosphorus.

A large number of models are available: mass balances models, black-box models or heuristic models, [1], [2], [3], [5], [6], [9], [10].

This paper presents a kinetic model of anaerobic digestion based on mass balance of substrate, microorganisms and methane production. The model is simulated using a customized Simulink model and the value of maximum specific growth rate of microorganisms is calibrated to fit the theoretical results with experimental ones regarding methane production.

2 Mathematical model

A single stage model it is developed in this paper to describe anaerobic kinetics. Usually, the anaerobic digestion involves several stages, every stage conducted by specific microorganisms. Only some of them limit the process, because of their slow growth. In order to investigate the kinetics of biogas production the process of anaerobic digestion has to considered the growth of microorganisms, the substrate degradation and the formation of final products, mainly biogas, C

For modeling purpose, the biological reactor can be considered as a closed tank with the following hypothesis taken into account:

- biochemical reactions occur only in the bioreactor;
- complete mixing for sludge and microorganisms and also for temperature in order to maintain 36⁰C in the bioreactor,
- steady-state regime

It is considered a schematic representation of a bioreactor with volume V (fig.1):

- the inlet of sludge: Q_{ni} – flowrate of the sludge, S_i – concentration of the substrate at the entrance, X_i – concentration of the anaerobic microorganisms at the entrance
- the outlet of digested sludge: Q_{ne} – flowrate of the digested sludge; S_e – concentration of the substrate at the outlet; X_e - concentration of the anaerobic microorganisms at the outlet
- biogas collection: Q_g – biogas flowrate; Z – methane concentration in biogas.

The mathematical model for the microorganisms growth, the substrate decomposition and biogas formation is based on the mass conservation law. In non-steady-state conditions, taking into account complete mixing in bioreactor and neglecting endogenous decay of the microorganisms, the equations for the mass balance of the

microorganisms, of the substrate and respectively of the methane formation in control volume, can be written as:

$$V \frac{dS}{dt} = Q_{ni} S_i - Q_{ne} S_e - r_n V \quad (1)$$

$$V \frac{dX}{dt} = Q_{ni} X_i - Q_{ne} X_e + r_c V - r_d V \quad (2)$$

$$V \frac{dZ}{dt} = Q_{ni} Z_i - Q_{ne} Z_e + K V \quad (3)$$

where: r_n – substrate degradation rate; r_c – growth rate of anaerobic microorganisms; r_d – decay rate of anaerobic microorganisms; K – coefficient that takes into account the transformation of volatile organic compounds in methane.

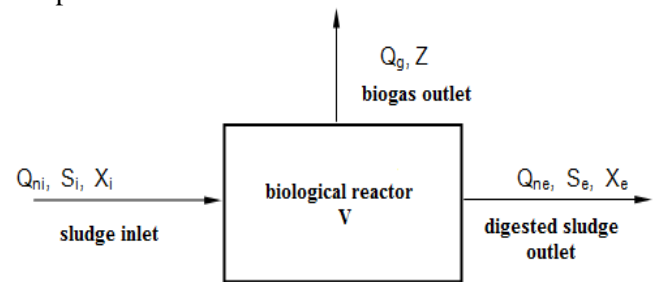


Fig.1. Schematic representation of the anaerobic bioreactor

The following assumptions are made:

- $Q_{ni} \cdot Z_{ni} = 0, Q_{ne} \cdot Z_{ne} = 0$
- $Q_{ni} = Q_{ne} = Q$
- $D = Q/V$ – dilution rate

and the equations (1), (2) and (3) become:

$$\frac{dX}{dt} = D \cdot (X_i - X_e) + r_c - r_d \quad (4)$$

$$\frac{dS}{dt} = D \cdot (S_i - S_e) - r_n \quad (5)$$

$$\frac{dZ}{dt} = K \quad (6)$$

The equation for the mass balance of the microorganisms can be written:

$$\frac{dX}{dt} = D \cdot (X_i - X_e) + \mu \cdot X - K_d \cdot X \quad (7)$$

where μ - specific growth rate of microorganisms and K_d – decay rate of microorganisms.

For the specific growth rate of microorganisms the Andrews relations is used, that takes into account substrate inhibition, [8]:

$$\mu = \mu_{\max} \frac{1}{1 + \frac{K_s}{S} + \frac{S}{K_i}} \quad (8)$$

The substrate degradation has to take into account the needs of the microorganisms, [3]:

- new cells formation:

$$r_{nx} = -\frac{1}{Y_x} \cdot \frac{dX}{dt} = -\frac{\mu \cdot X}{Y_x} \quad (9)$$

Y_x – yield coefficient

- energy supply for the growth and maintain of microorganisms:

$$r_{np} = K_{sx} \cdot X \cdot \mu + K_{mx} \cdot X \cdot \frac{S}{K_s + S} \quad (10)$$

K_{sx} – substrate degradation rate to supply energy for microorganisms growth, K_{mx} - substrate degradation rate to supply energy for microorganisms maintain

- products formation, for example methane:

$$r_{nc} = \frac{1}{Y_s} \cdot \frac{dZ}{dt} \quad (11)$$

Y_s – methane production coefficient.

Mass balance equation (5) for substrate becomes:

$$\frac{dS}{dt} = D \cdot (S_i - S_e) - \frac{\mu \cdot X}{Y_x} - K_{sx} \cdot X \cdot \mu - K_{mx} \cdot X \cdot \frac{S}{K_s + S} - \frac{1}{Y_s} \cdot \frac{dP}{dt} \quad (12)$$

Converting organic compounds in methane depends on the microorganisms growth, so that for the K coefficient can be used the relation:

$$K = Y_p \cdot \mu \cdot X \quad (13)$$

Y_p – coefficient that takes into account conversion of organic compounds in methane.

The equation (6) for methane production can be written:

$$\frac{dZ}{dt} = Y_p \cdot \mu \cdot X \quad (14)$$

3 Simulation results

The equations (7), (12) and (14) are used for theoretical simulation of microorganisms, substrate and methane concentrations in time. A customized model was developed in Matlab-Simulink, fig.2, using standard blocks from the Simulink library, [8]. The simulation input data were obtain during 3 months measurements campaign in 2010 at Wastewater Treatment Plant Contanța South, Romania. From the 4 digesters of the plant only 3 of them were in operation. Biogas flowrate was measured for 2 of them and for the third the flowrate was calculated using extrapolation. For the modeling purpose it is considered only 1 digester with the volume triple as the volume of one digester: $V = 3 \times 4000 = 12\,000\text{ m}^3$. The inlet sludge flowrates for the 3 months are $350\text{ m}^3/\text{d}$, $298\text{ m}^3/\text{d}$ and $312\text{ m}^3/\text{d}$. Thus, the dilution rates are 0.0292 d^{-1} ,

0.02843 d^{-1} and 0.026 d^{-1} . Retention time is considered 30 days.

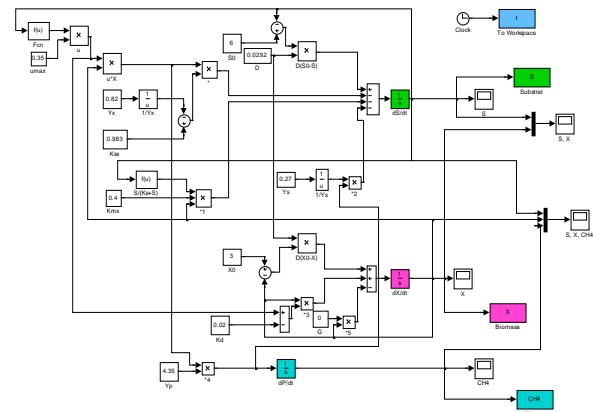


Fig. 2. Simulink model for simulation of anaerobic kinetics

According to romanian standard NP118-06, [11], only 60-75% of the inlet sludge represents organic compounds. Thus, considering an average value of 8.38 g/l COD in influent sludge, as it was measured, only 5 g/l is organic matter, and this value is taken into account for inlet substrate concentration.

Initial conditions for substrate concentration is $S_0 = 6\text{ g/l}$ and for microorganisms concentration $X_0 = 3\text{ g/l}$.

For kinetic coefficients it is used the values from the literature, [3], [4], [9], [10]:

$\mu_m = 0.2...1.2\text{ d}^{-1}$; $K_s = 7.1...360\text{ mg/l COD}$; $K_d = 0.02...0.04\text{ d}^{-1}$; $K_i = 0.5, 1.0, 10.0, 100.0$; $Y_x = 0.3...0.82$; $Y_s = 0.04...0.27$; $Y_p = 4.35$; $K_{mx} = 0.4$; $K_{sx} = 0.983$.

The simulation data represent variation in time of methane concentration and measurements data represent biogas flowrate. In order to compare the results it is considered that 60% in biogas is methane and using methane density, $\rho_{CH_4} = 0.717\text{ kg/m}^3$, it is calculated methane flowrate:

$$Q_{CH_4} [kg / d] = Q_{biogas} [m^3 / d] \cdot 0.6 \cdot 0.717 \quad (15)$$

Mass of methane produced in the simulation time is:

$$M_{CH_4} [kg] = Q_{CH_4} [kg / d] \cdot 30d \quad (16)$$

The concentration of methane will be:

$$Z [g / l] = M_{CH_4} [kg] / V [m^3] \quad (17)$$

The simulations were done for dilution rates $D = 0,0292\text{ d}^{-1}$, $D = 0,02483\text{ d}^{-1}$ and $D = 0,026\text{ d}^{-1}$, according with experimental measurements. For every dilution rate there was realized simulations for three values of the specific growth rate of microorganisms: $\mu_m = 0.35\text{ [d}^{-1}]$, $\mu_m = 0.38\text{ [d}^{-1}]$ and $\mu_m = 0.4\text{ [d}^{-1}]$.

Some of the results of the simulations for May, June and July 2010 are presented in fig. 3 – 21.

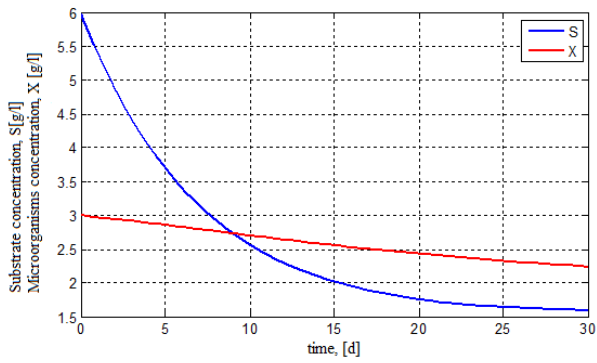


Fig.3. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.35 \text{ [d}^{-1}\text{]}$ and $D= 0.0292 \text{ [d}^{-1}\text{]}$

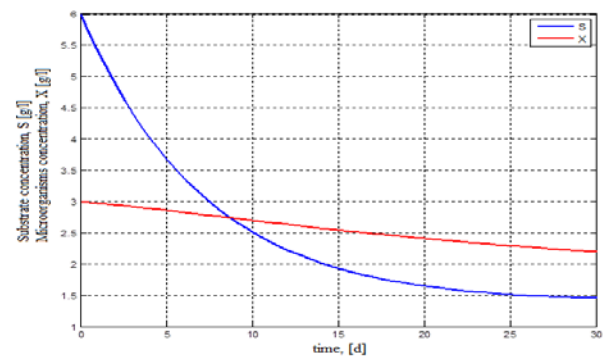


Fig.7. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.35 \text{ [d}^{-1}\text{]}$ and $D= 0.02483 \text{ [d}^{-1}\text{]}$

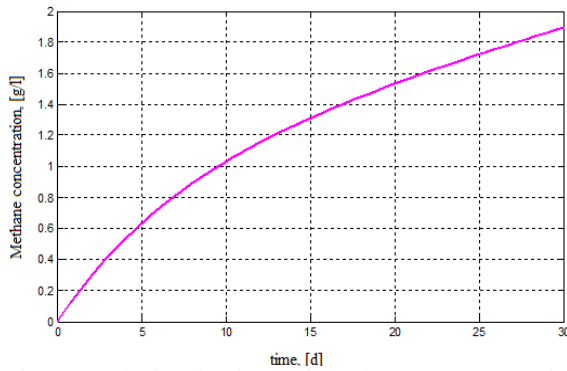


Fig.4. Variation in time of methane concentration for $\mu_m = 0.35 \text{ [d}^{-1}\text{]}$ and $D= 0.0292 \text{ [d}^{-1}\text{]}$

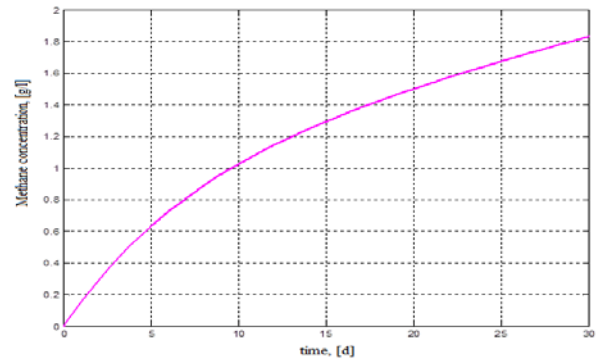


Fig.8. Variation in time of methane concentration for $\mu_m = 0.35 \text{ [d}^{-1}\text{]}$ and $D= 0.02483 \text{ [d}^{-1}\text{]}$

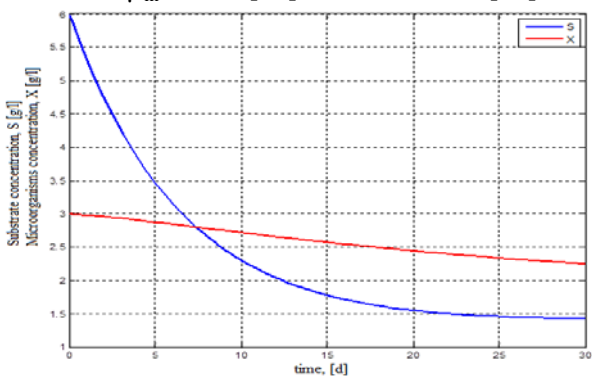


Fig.5. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.4 \text{ [d}^{-1}\text{]}$ and $D= 0.0292 \text{ [d}^{-1}\text{]}$

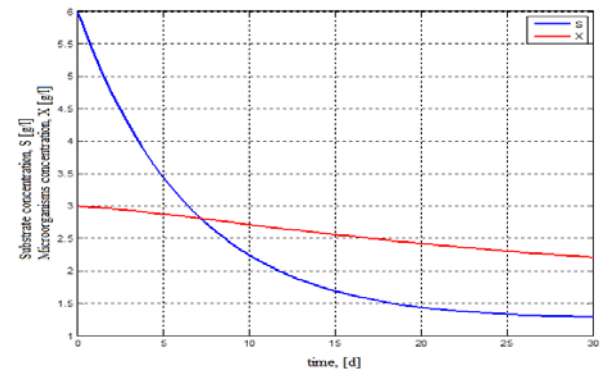


Fig.9. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.4 \text{ [d}^{-1}\text{]}$ and $D= 0.02483 \text{ [d}^{-1}\text{]}$

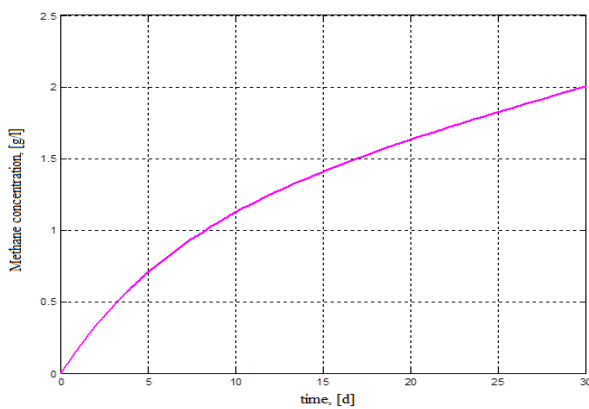


Fig.6. Variation in time of methane concentration for $\mu_m = 0.4 \text{ [d}^{-1}\text{]}$ and $D= 0.0292 \text{ [d}^{-1}\text{]}$

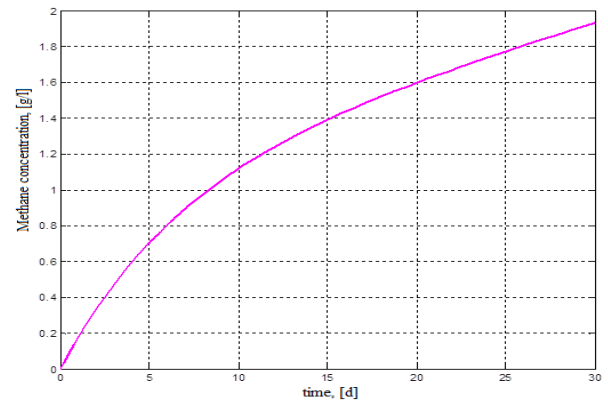


Fig.10. Variation in time of methane concentration for $\mu_m = 0.4 \text{ [d}^{-1}\text{]}$ and $D= 0.02483 \text{ [d}^{-1}\text{]}$

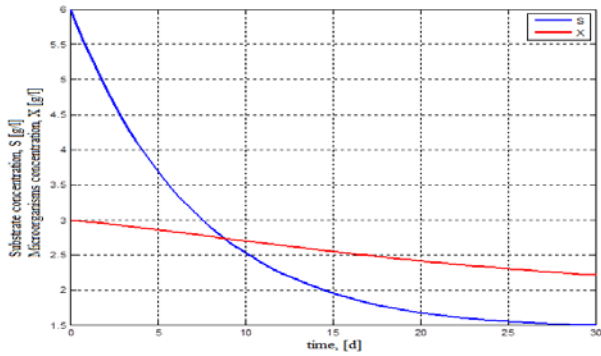


Fig.11. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.35 [d^{-1}]$ and $D = 0.026 [d^{-1}]$

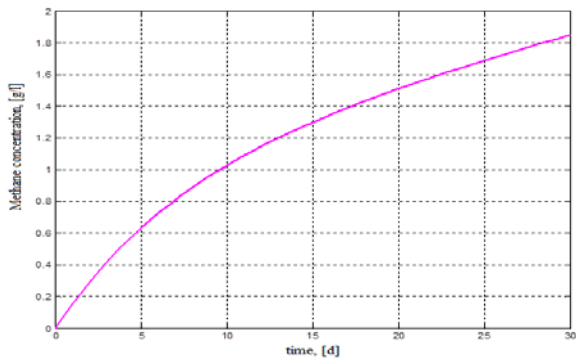


Fig.12. Variation in time of methane concentration for $\mu_m = 0.35 [d^{-1}]$ and $D = 0.026 [d^{-1}]$

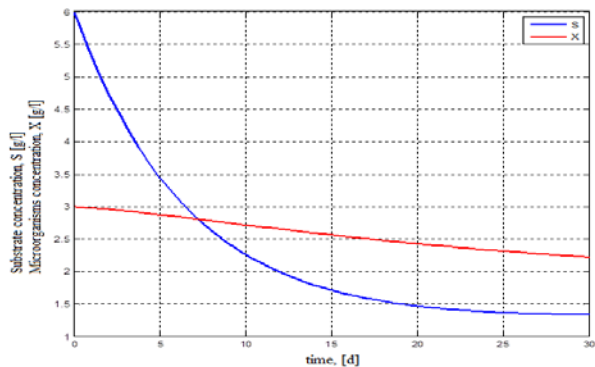


Fig.13. Variation in time of substrate and microorganisms concentrations for $\mu_m = 0.4 [d^{-1}]$ and $D = 0.026 [d^{-1}]$

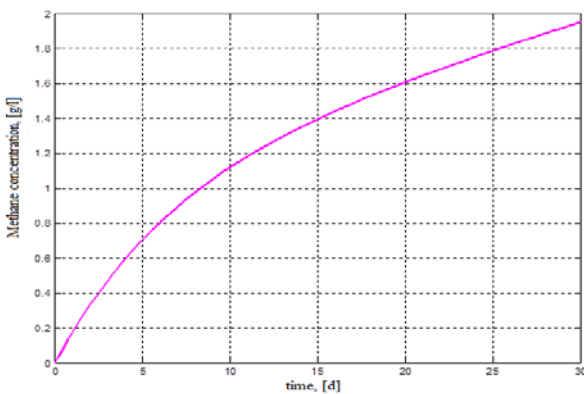


Fig.14. Variation in time of methane concentration for $\mu_m = 0.4 [d^{-1}]$ and $D = 0.026 [d^{-1}]$

According to the results presented in the Table 1 the specific maximum growth rate of microorganisms was calibrated at the values $\mu_m = 0.35 [d^{-1}]$. For this value simulation data best fit the experimental ones.

Table 1

	May	June	July
Experimental data			
Inlet sludge flowrate $Q_{ni} [m^3/d]$	350	298	312
Biogas flowrate $Q_{biogas} [m^3/d]$	1920	2246	1557
Dilution rate $D [d^{-1}]$	0.0292	0.02483	0.026
Methane mass production in 30 days, $M_{CH_4} [kg]$	826	966.23	669.82
Methane concentration $Z [g/l]$	2.065	2.41	1.6746
Simulation data			
$\mu_m = 0.35 [d^{-1}]$			
Methane mass flowrate $Q_{CH_4} [kg/d]$	1920.037	2231.52	1552.77
Methane mass production in 30 days, $M_{CH_4} [kg]$	826	960	668
Methane concentration $Z [g/l]$	2.065	2.4	1.67
$\mu_m = 0.38 [d^{-1}]$			
Methane mass flowrate $Q_{CH_4} [kg/d]$	1813.11	1766.62	1766.62
Methane mass production in 30 days, $M_{CH_4} [kg]$	780	760	760
Methane concentration $Z [g/l]$	1.95	1.9	1.9
$\mu_m = 0.4 [d^{-1}]$			
Methane mass flowrate $Q_{CH_4} [kg/d]$	1859.6	1794.51	1813.11
Methane mass production in 30 days, $M_{CH_4} [kg]$	800	772	780
Methane concentration $Z [g/l]$	2	1.93	1.95

4 Conclusion

Modeling anaerobic digestion is very complicated because of the unsteady state behavior and the interaction of different nature of the parameters involved. The paper presents a simple single stage mathematical model for anaerobic digestion kinetics based on the mass balance equations. Simulation studies were conducted using input data obtained during a three months measurements campaign in 2010 in Wastewater Treatment Plant Constanta South, Romania. Simulated results obtained using a customized Simulink model are used to calibrate the maximum growth rate of microorganisms so that the simulation results best fit the experimental ones.

References:

- [1] Batstone D.J., Keller J., Angelidaki I., Kalyuzhnyi S.V., Pavlostathis S.G., Rozzi A., Sanders W.T.M. *, Siegrist H., Vavilin V.A.. The IWA Anaerobic Digestion Model No 1 (ADM1), *Water Science & Technology*, Vol. 45, No. 10, 2002, pp 65–73.
- [2] Dimitrova N., Krastanov M. Nonlinear adaptive stabilizing control of an anaerobic digestion model with unknown kinetics, *International Journal of Robust and Nonlinear Control Published online in Wiley Online Library* (wileyonlinelibrary.com), 2011.
- [3] Gerber M., Span R. *An Analysis of Available Mathematical Models for Anaerobic Digestion of Organic Substances for Production of Biogas*, International Gas Research Conference, Paris, 2008.
- [4] Metcalf & Eddy Inc., *Wastewater Engineering. Treatment and Reuse. Fourth edition*, 2003
- [5] Siegrist H., Vogt D., Garcia – Heras J.L., Gujer W. Mathematical Model for Meso- and Thermophilic Anaerobic Sewage Sludge Digestion, *Environmental Science and Technology*, 2002, 36, pp. 1113-1123.
- [6] Simeonov I., Diop S. Stability Analysis of Some Nonlinear Anaerobic Digestion Models, *International Journal of Bioautomation*, 2010, 14(1), 37-48.
- [7] Robescu D., Lanyi S., Robescu Diana, Constantinescu I., Verestoy A., *Wastewater Treatment Technologies, Installations and Equipment (in Romanian)*, Technical Publishing House, Bucharest, 2001.
- [8] Robescu Diana, Lanyi S., Verestoy A., Robescu D., *Modeling and simulation of wastewater processes (in Romanian)*, Technical Publishing House, Bucharest, 2004.
- [9] Tomei M.C., Braguglia C.M., Cento G., Mininni G. Modeling of Anaerobic Digestion of Sludge, Critical Reviews. *Environmental Science and Technology*, 2009, pp. 1003-1051.
- [10] Wiesmann U., Su Choi I., Dombrowski E.M., *Fundamentals of biological wastewater treatment*, Wiley-VCH, 2007.
- [11] ***. *Regulatory design of buildings and installations for municipal wastewater treatment – 5th part: Sludge Handling (in Romanian) -Normativ pentru proiectarea construcțiilor și instalațiilor de epurare a apelor uzate orășenști – Partea a V-a: Prelucrarea nămolurilor*), NP118-06.