

MATHEMATICAL MODEL FOR FOOD INDUSTRY WASTEWATER TREATMENT PROCESSES

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ABSTRACT

The purpose of this paper is to obtain a mathematical model for a food industry wastewater treatment pilot plant based on ASM1 model. It aims to establish a simplified model, which allows the implementation of advanced control strategies of the process. For parameters identification and sensitivities analysis with AQUASIM software were used datasets from the pilot plant for wastewaters taken from the dairy industry. As a result of the sensitivity analysis only two parameters were considered for identification: maximum specific growth rate for heterotrophs and yield for heterotrophs. Results obtained on different datasets have shown a good concordance between the experimental data and the data obtained through model simulation. Finally the model determined in the paper was subjected to a modal analysis in different operating points of the process. This has lead to a simplified model better suited for implementing different advanced control strategies of the process in order to improve the wastewater treatment system efficiency.

1 INTRODUCTION

Water is one of the most important resources of life. Wastewater treatment had become a necessity in a highly populated industrialized world and every producer must improve with responsibility their treatment processes. Increasing the efficiency of these processes was done in two ways: by technological ways and by using control methods – which currently represent a real challenge for researchers.

Wastewater treatment processes consist of a series of physical, chemical or biological processes that allow the separation between some particles (solid or dissolved, organic compounds, minerals etc.) and water, aiming to obtain a "clean" water able to meet certain standards for discharge or domestic/industrial consumption. In general, the operational objective for a wastewater treatment plant is to achieve the required effluent standards with least operational costs (Olsson et al. (2005)).

The treatment rules of waters coming from different industries are not the same. They depend on the receiving water and the type of the industry from which the wastewater results. Wastewater treatment is accomplished most economically by processes with biological oxidation, and among them, the activated sludge process is the most generally applied biological wastewater purification technique.

Wastewater process modeling can enhance projects involving an entire range of wastewater treatment processes, including physical-chemical; biological, such as

activated sludge; and solids, such as thickening, digestion, and dewatering. Models in biological wastewater treatment, as for any industrial process, have always played an important role in the process design and in determining the control and operating strategies. The Activated Sludge Models (ASMs) presented by the International Water Association (IWA) (Henze et al. (2000)) are generally accepted as the mathematical description of the biochemical processes in the activated sludge process reactors.

The activated sludge processes are the most generally applied biological wastewater purification technique and attracts a great deal of attention from the research community. Modeling of activated sludge process has become a common part of the design and operation of wastewater treatment plants, being a very active research area (e.g. Dochain & Vanrolleghem (2001) and Hu et al. (2003)). Today, models are being used in design, control, teaching and research. Process models are essential tools for understanding wastewater treatment system behavior.

However, a relatively recent trend is software developments supporting open component-based architectures and reuse of components based on object-oriented methods (see Heck et al. (2003)). There exist some computer programs dedicated to the development and validating of wastewater treatment process, among them: AQUASIM, SIMBA, WEST, BioWin, GPS-X and Modelica. The models are or can be built-in. There are procedures for characterization of wastewater and sludge and the protocol for the development of calibrated activated sludge models.

In the literature there are many models that try to capture as closely as possible the evolution of the wastewater treatment processes with activated sludge (Henze et al. (1987), (1995), (2000)). The modeling of these processes is made globally, considering the nonlinear dynamics, but in order to develop control algorithms simplify models has to be used (Barbu (2009)). Among the features that make these processes real challenges for the specialist in control (see Olsson & Newell (1999) and Olsson et al. (2005)) one can find: requirement of a proper dynamic model to describe the complex system that incorporate a large number of biological and biochemical processes and uncertain model parameters (Goodman & Englande (1974)) due to the varying operation, influent, and sludge characteristics of the process, low repeatability rate, slow responses and the lack or high cost of the measuring instruments for the state variables of bioprocesses (biomass concentration, COD concentration etc.).

Finally, it should be recognized that modeling is an essential part of research which expand our knowledge.

In the present paper the authors proposes to obtain a reduced mathematical model order for a wastewater treatment process starting from the ASM1 model (Activated Sludge Model 1) determined by a work group belonging to IAWQ (International Association of Water Quality) and using experimental data from a food industry wastewater treatment pilot plant. The obtained simplified model will be easier to use for the implementation of advanced automatic control algorithms in order to improve the wastewater treatment system efficiency.

The paper is structured as follows: the second section presents the pilot plant from "Dunărea de Jos" University of Galati. In section 3 are presented aspects regarding wastewater treatment process modeling. Subsection 3.1 briefly describes the ASM1 model for wastewater treatment process and in subsection 3.2 is presented the simplified version of ASM1 model obtained taking into consideration only three processes from the ASM1 general model as a result of experiments which were carried out on the plant

in different operating conditions. The forth section deal with modal analysis of the transfer functions from the two loops of the simplified model: substrate and dissolved oxygen concentration loop. Mathematical model identification results with Aquasim software are presented in the fifth section. Further is the section dedicated to the conclusions and in the end of the paper are presented some acknowledgement.

2 WASTEWATER TREATMENT PILOT PLANT

A wastewater treatment pilot plant which is completely controlled by the computer (Figure 1) was conceived for studying and implementing various control algorithms during a research national project managed by “Dunărea de Jos” University of Galati. The objective of the pilot plant is to improve the efficiency of the biological treatment processes in case of various types of wastewaters from food industry in aerobic conditions.

The feeding tank [1] has the capacity of 0.1 m^3 and the ability to maintain the wastewater inside at almost constant characteristics due to its refrigeration equipment ($1 - 6 \text{ }^\circ\text{C}$). The feeding flow can be strictly controlled through a peristaltic pump with a $0.288 \text{ m}^3/\text{day}$ maximum flow. Before being pumped into the tanks the wastewater can be heated in a small expansion tank. The aeration tank [2] is the heart of the biological treatment process. Here the wastewater is mixed with the activated sludge and to fulfill the process it is also mixed with air. The air is bubbled into the aeration tank through a set of air ejectors which have also a mixing role. To be able to control the medium homogeneity the aeration tank is also equipped with a mechanical paddle mixer with three working regimes: 60 rpm, 180 rpm and 300 rpm. The aeration tank working volume is 0.04 m^3 . The treatment temperature can be online monitored and controlled through a temperature probe and an electric heating resistance both mounted inside the tank. The pH can also be online monitored and controlled through a pH electrode connected to a pH controller and two peristaltic pumps, one for acid and the other for base (acid tank [3] and base tank [4]). The turbidity can be online monitored with a dedicated optical electrode. The evolution of the biomass can be indirectly estimated through the turbidity values; the correlation between the two variables is usually made offline by measuring the sludge dry matter. The aeration tank is also provided with an ORP (Oxide-Reduction Potential) transducer. The ORP potential can be correlated, in some cases, with the COD of the wastewater. The anoxic tank [5] can be used in the advanced nitrification – denitrification processes or it can be used in a sludge stabilization stage. In our experiments this tank remained unused. The sludge flocks formed in the aeration tank are allowed to settle in the clarifier [6]. This tank is provided with an ultrasonic level transducer which gives the flexibility to work at different retention times according to the chosen treatment scheme. From the bottom of the clarifier the settled sludge is recycled with a peristaltic pump back into the aeration tank.

One of the most important variables in an aerobic treatment process is the DO (dissolved oxygen concentration) which is controlled by a cascade control structure. The cascade control system contains an inner loop (air flow control loop) that has a fast dynamics and an outer loop (the DO control loop) that has slower dynamics.



Figure 1. Wastewater treatment pilot plant from “Dunarea de Jos” University of Galati

The air flow is on-line measured with a flow meter and it is controlled with an electric continuous valve. The maximum air flow rate is 43.23 m³/day. The DO concentration is on-line measured with an electrochemical electrode mounted in the aeration tank and it is controlled using the aeration rate as a control variable. The transducer signals are captured by a PCI data acquisition board. A HMI (*Human-Machine Interface*) facilitates the process control and monitoring. The data can be stored in a data base and processed thereafter.

3 WASTEWATER TREATMENT PROCESS MATHEMATICAL MODELLING

This section deals with the wastewater treatment process modeling. In subsection 3.1 is presented the most popular model in literature of the wastewater treatment processes, the ASM1 model, also known under names like: IAWPRC model or IAWQ model (Henze et al. (1987)) and in subsection 3.2 a simplified version of ASM1 model is established, which allows the implementation of advanced control strategies of the process.

3.1 Activated Sludge Model 1 (ASM1)

The most frequently used activated sludge models are the family of Activated Sludge Models developed by the International Water Association (IWA). The Activated Sludge Model No. 1 (ASM1) is usually considered as the reference model, which was primarily developed to describe the removal of organic carbon substances and nitrogen.

In the extremely complex ASM1 model will be considered initially all eight phenomena occurring in the anoxic and aerated reactors which are presented in Table I and 12 state variables (alkalinity was not considered in the model) from the 13 independent state variables existing in ASM1 for each reactor compartmental (see Table

II). This requires the definition of a large number of initial values before integration may start (Henze et al. (2000)). The main deficiency of the model ASM1 is its complexity, making it virtually useless in control issues.

Table I. The eight phenomena occurring in the anoxic and aerated reactor

Process	Name of the process
P ₁	Aerobic growth of heterotrophs - the process converts readily biodegradable substrate, dissolved oxygen and ammonium in the heterotrophic biomass
P ₂	Anoxic growth of heterotrophs - the process converts readily biodegradable substrate, nitrate and ammonium in heterotrophic biomass
P ₃	Aerobic growth of autotrophs - the process converts the dissolved oxygen, and ammonium in autotrophic biomass
P ₄	Decay of heterotrophs - heterotrophic biomass is decomposed into slowly biodegradable substrate and other particles
P ₅	Decay of autotrophs - autotrophic biomass is decomposed into slowly biodegradable substrate and other particles
P ₆	Ammonification of soluble organic nitrogen - biodegradable organic nitrogen is converted to ammonium
P ₇	Hydrolysis of entrapped organics - slowly biodegradable substrate is converted into readily biodegradable substrate
P ₈	Hydrolysis of entrapped organic nitrogen - solid biodegradable organic nitrogen is converted into soluble biodegradable organic nitrogen

Table II. State variables of the ASM1 model

State variable	Name of the state variable
S _I	Soluble inert organic matter
S _S	Readily biodegradable soluble substrate
X _I	Various independent particles of inert organic matter and other particles
X _S	Readily biodegradable soluble substrate
X _{B,H}	Activated heterotrophic biomass
X _{B,A}	Activated autotrophic biomass
X _P	Different particles resulting from the biomass decomposition
S _O	Dissolved oxygen concentration;
S _{NO}	Soluble nitrate;
S _{NH}	Soluble ammonium;
S _{ND}	Soluble biodegradable organic nitrogen;
X _{ND}	Various particulate of biodegradable organic nitrogen;
S _{ALK}	Alkalinity

3.2 Simplified mathematical model

When modeling of wastewater treatment process, a certain number of simplifications and assumptions must be made in order to make the model tractable.

Some of them concern the mathematical model and others are associated with physical system itself.

During the experiments it was used wastewater collected from the dairy industry, water with low content of ammonium. For that reason, has been used only the aerated basin, not being necessary to use the anoxic basin. The clarifier model was determined making the following assumptions: into the clarifier wastewater treatment processes don't take place, a part of sludge is recycled and the sludge in excess is removed from the system.

Under these conditions, the simplified model has three processes (Aerobic growth of heterotrophs, Decay of heterotrophs and Hydrolysis of entrapped organics) plus bioreactor aeration and sludge removal, and five state variables (S_S , X_S , $X_{B,H}$, X_P and S_O).

The simplified ASM1 model is described by the following equations:

$$\frac{dS_S}{dt} = \frac{-1}{Y_H} \cdot P_1 + P_7 + \frac{Q_{in}}{V} \cdot S_{Sin} - \frac{Q_{in}}{V} \cdot S_S \quad (1)$$

$$\frac{dX_S}{dt} = (1 - f_P) \cdot P_4 - P_7 + \frac{Q_{in}}{V} \cdot X_S \quad (2)$$

$$\frac{dX_{B,H}}{dt} = P_1 - P_4 - \frac{Q_{in}}{V} \cdot X_{B,H} \quad (3)$$

$$\frac{dX_P}{dt} = f_P \cdot P_4 - \frac{Q_{in}}{V} \cdot X_P \quad (4)$$

$$\frac{dS_O}{dt} = -\frac{1 - Y_H}{Y_H} \cdot P_1 + W \cdot K_{LA} \cdot (DO_{max} - S_O) - \frac{Q_{in}}{V} \cdot S_O \quad (5)$$

$$P_1 = \hat{\mu}_H \cdot \left(\frac{S_S}{K_S + S_S} \right) \cdot \left(\frac{S_O}{K_{O,H} + S_O} \right) \cdot X_{B,H} \quad (6)$$

$$P_4 = b_H \cdot X_{B,H} \quad (7)$$

$$P_7 = k_h \cdot \left(\frac{X_S}{K_X \cdot X_{B,H} + X_S} \right) \cdot \left(\frac{S_O}{K_{O,H} + S_O} + \eta_h \cdot \frac{K_{O,H}}{K_{O,H} + S_O} \right) \cdot X_{B,H} \quad (8)$$

The input process variables are: aeration rate, W and wastewater flow, Q_{in} and the output measurable variables are: dissolved oxygen concentration in the aerated tank, S_O and readily biodegradable substrate, S_S .

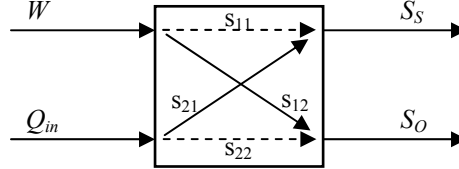
For the model described by equation (1)-(8), the parameters from Table III were taken into consideration. Besides these values, were also considered: $K_{LA}=0.094$ [g/m³], $Q_{in}=0.0528$ [m³/day], $Q_{recirc}=0.0132$ [m³/day], $DO_{max}=10$ [gO₂/m³] and $S_{Sin}=1924$ [gO₂/m³].

Table III. Typical parameters values at neutral pH

Symbol	Unit	Value at 20 °C
Stoichiometric parameters		
Y_H	(g COD oxidized) ⁻¹	0.536
f_p	dimensionless	0.08
Kinetic parameters		
$\hat{\mu}_H$	day ⁻¹	1.19
K_S	gCOD/m ³	20
$K_{O,H}$	gO ₂ /m ³	0.2
b_H	day ⁻¹	0.62
η_g	dimensionless	0.8
η_h	dimensionless	0.4
k_h	(g cell COD day) ⁻¹	3.0
K_X	(g cell COD) ⁻¹	0.03

4 MODAL ANALYSIS OF THE ASM1 SIMPLIFIED MODEL

The simplified model obtained from customizing the ASM1 general model for experimental conditions, has the general structure shown in Figure 2.


Figure 2. General structure of the ASM1 simplified model

In order to develop an automatic control strategy relations (1)-(8) were implemented in Matlab/Simulink and *linmod* function was used to obtain the four transfer functions (s_{11} , s_{22} , s_{12} and s_{21}) of the model shown in Figure 2. Initially, for the s_{12} and s_{21} were obtained 5-order models. A modal analysis was done in order to reduce these transfer functions to a first order transfer function. The mathematical values of these transfer functions obtained through *linmod* are given in relations (9) – (10) and the reduced first order form in relations (11)-(12).

$$s_{12} = \frac{34.14s^4 + 1432s^3 + 6567s^2 + 1.05 \cdot 10^4 s + 5608}{s^5 + 1484s^4 + 60430s^3 + 2.566 \cdot 10^5 s^2 + 3.756 \cdot 10^5 s + 1.832 \cdot 10^5} = \frac{44.1306}{s + 1442} \quad (9)$$

$$s_{21} = \frac{4.47 \cdot 10^4 s^4 + 6.624 \cdot 10^7 s^3 + 2.586 \cdot 10^9 s^2 + 7.13 \cdot 10^9 s + 5.059 \cdot 10^9}{s^5 + 1484s^4 + 60430s^3 + 2.566 \cdot 10^5 s^2 + 3.756 \cdot 10^5 s + 1.832 \cdot 10^5} = \frac{53534}{s + 1.939} \quad (10)$$

$$s_{12red} = \frac{44.1306}{s + 1442} \quad (11)$$

$$s_{21red} = \frac{53534}{s + 1.939} \quad (12)$$

Analysing these relations, one can see that the time constants of the two processes (for the substrate and for the dissolved oxygen transfer function) are very different: $T_{12}=6.9348 \cdot 10^{-4}$ days and $T_{21}=0.515$ days. This result shows that they can be analysed separately in terms of automatic control.

For validation of the reduced-order models (relations (11)-(12)) were represented in Figure 3 Bode diagrams of the 5-th order transfer functions s_{12} and s_{21} from relations (9)-(10) and their first order model obtained from modal analysis, i.e. relations (11) and (12).

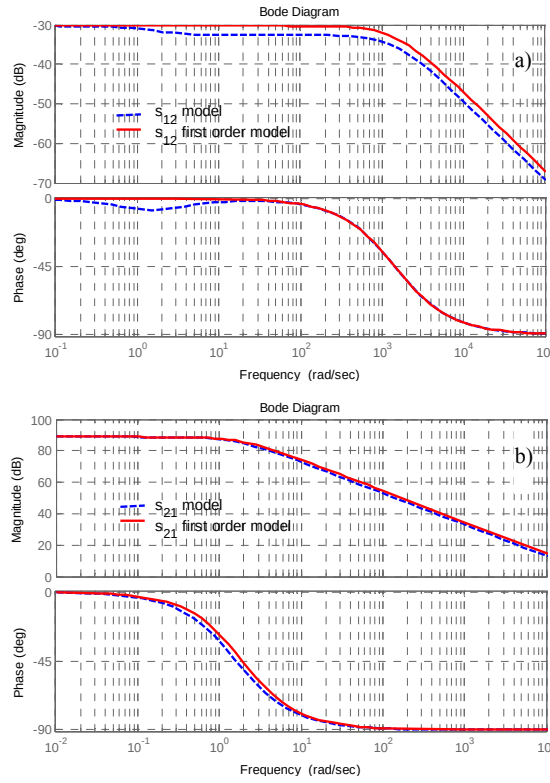


Figure 3. Bode diagrams of the two processes initial models and with their first order models obtained through modal analysis: a) s_{12} from equation (9) with s_{12red} from (11); b) s_{21} from equation (10) with s_{21red} from (12)

5 EXPERIMENTAL IDENTIFICATION OF THE MATHEMATICAL MODEL

5.1 Identification of the DO (dissolved oxygen) loop transfer function

The experiment was carried out in the following conditions:

- the wastewater inflow was maintained constantly during the two monitoring days, at 0.0528 m³/day;
- the pH was not controlled, but it was continuously monitored using a dedicated transducer with measuring domain: 0 ÷ 14 pH units;
- active sludge from yeast company Rompak-Pascani (Romania) was used as inoculum. The sludge amount was 0.5 L, with an optical density, measured at 600 nm, equal to 9.7;
- diluted whey in a concentration of 1:40 with drinking water and having an initial concentration equal to 1924 gCOD/m³ has been used;
- the dissolved oxygen concentration was continuously measured using the dedicated transducer;
- COD (chemical oxygen demand) was determinate twice/day;
- the turbidity in the aerated tank was continuously monitored using a dedicated transducer; the measuring domain is 0 ÷ 3000 NTU;
- the wastewater turbidity was measured once/day; it is expressed in NTU;
- the total nitrogen (N_{tot}) was measured once/day;
- phosphate (P-PO₄³⁻) was measured once/day;
- the nitrogen from nitrates (NO₃) was measured once/day;
- the redox potential (ORP) was continuously monitored using a dedicated transducer; the measuring domain is -1000 ÷ +1000 mV;
- the temperature was maintained constantly at 25 °C;
- the volume of bubbled air: three regimes of 7.2, 11.52 and 14.4 m³/day were used;
- the air flow was monitored using a flow transducer installed on the air network; the measuring domain is 0 ÷ 50 m³/day;
- the stirring rate was maintained constantly at 300 rpm.

The aerated tank was fed continuously with a culture medium using a peristaltic pump having a maximum flow value equal to 0.288 m³/day. The settled sludge to the settler bottom was recycled with a flow of 3.456 m³/day.

Evolutions of main variables monitored during two days of experiments realized in the above conditions, are represented in Figure 4.

In order to improve the efficiency of wastewater treatment system through different control laws, an identification of the dissolved oxygen loop transfer function was done. A negative step was applied on the input (aeration rate) from 14.4 m³/day to 11.52 m³/day and was analyzed the evolution of the output variable (concentration of dissolved oxygen). This step was applied at time t=0.8 days, as one can see from Figure 4.

From Figure 4 one can see that the evolution of dissolved oxygen when it is applied a negative step of input, is similar with one of an aperiodic component. Under these conditions, the following loop transfer function of the dissolved oxygen was resulted:

$$H(s) = \frac{0.82}{0.0243s + 1} = \frac{K}{Ts + 1} \quad (13)$$

where K is the amplification factor and T is the time constant.

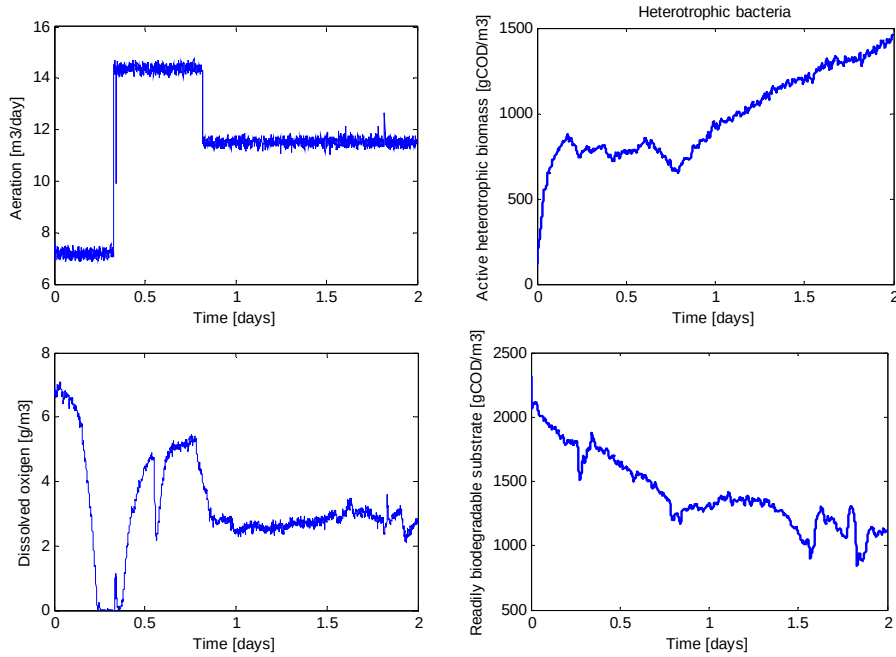


Figure 4. Evolutions of principal variables of the experimental plant

5.2 Implementing the model in Aquasim

Aquasim is a computer program for the identification and simulation of aquatic systems. Comparison of measurements with model calculations is the most important method of testing theories in the natural sciences. Most mathematical models of environmental systems consist of a set of nonlinear ordinary or partial differential equations. A computer program which solves these equations numerically is usually required for calculating model predictions. Aquasim is extremely flexible in allowing the user to specify transformation processes, and, in addition to performing simulations for the user-specified model, it provides elementary methods for parameter identifiability analysis, for parameter estimation and for uncertainty analysis (Henze et al. (2000)).

The first step in obtaining a model for wastewater treatment processes from dairy industry is the analysis of parameter sensitivities. In this case, the dissolved oxygen loop is treated separately, dissolved oxygen concentration is not a state variable, but a constant parameter. The following parameters have been considered: maximum specific growth rate for heterotrophic biomass (μ_H), yield for heterotrophic biomass (Y_H), maximum specific growth rate for autotrophic biomass (μ_A), decay coefficient for heterotrophic biomass (b_H) and maximum specific hydrolysis rate (k_h). The choice of these parameters has been done based on the parameters of the model ASM1 that are pointed out for their measuring. The parameters with satisfactory values were not taken into consideration, because their measure is not necessary. As a result of the sensitivity analysis only two parameters will be considered for identification: maximum specific growth rate for heterotrophic biomass (μ_H) and yield for heterotrophic biomass (Y_H).

5.3 Identification of Aquasim model parameters based on experimental data

For identification of Aquasim model parameters based on experimental data were used standard parameters from ASM1 simplified model, among real values from experiments for dissolved oxygen concentration, readily biodegradable substrate, aeration rate and active heterotrophic biomass. The water from the experiment was taken from dairy industry.

In Figure 5 are represented results obtained from simplified ASM1 model implemented in Aquasim, for which were used real values from the experiments performed on the pilot plant from our university. Results obtained on different datasets have shown a good concordance between the experimental data and the data obtained through model simulation (see Figure 5).

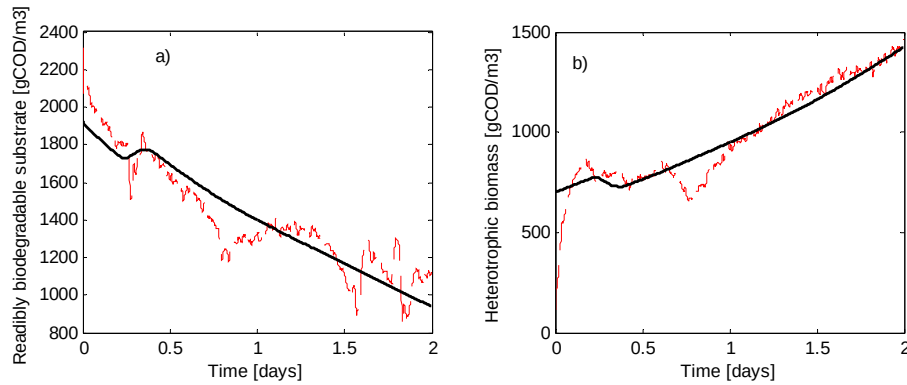


Figure 5. Results obtained with simplified ASM1 model implemented in Aquasim: a) Readily biodegradable substrate (Aquasim result - solid line, experimental result – dashed line); b) heterotrophic biomass (Aquasim result - solid line, experimental result – dashed line)

From Figure 5 one can see that the obtained simplified model is properly calibrated and predict process behavior including changes in and quantifications of readily biodegradable substrate and heterotrophic biomass.

Once the parameter values have been calibrated to a particular wastewater to minimize observable discrepancies between field data and model predictions, a model may be used by the engineer to eliminate inefficient designs, to choose those alternative configurations which are most likely to be economic and to develop different automatic control strategies.

6 CONCLUSIONS

It was obtained a simplified model based on ASM1 general model (with eight processes and 13 independent state variables) customized for specified working conditions of wastewater treatment from dairy industry and implemented in Aquasim software. The obtained simplified model has only three processes (Aerobic growth of heterotrophs, Decay of heterotrophs and Hydrolysis of entrapped organics) plus bioreactor aeration and sludge removal. Also, the number of state variables is smaller (only five state variables: S_S , X_S , $X_{B,H}$, X_P and S_O) than in case of ASM1 model.

For parameters identification and sensitivities analysis with AQUASIM software were used datasets from the pilot plant for wastewaters taken from the dairy industry. As a result of the sensitivity analysis only two parameters were considered for identification: maximum specific growth rate for heterotrophs and yield for heterotrophs. Results obtained on different datasets have shown a good concordance between the experimental data and the data obtained through model simulation. Finally the model determined in the paper was subjected to a modal analysis in different operating points of the process. This has lead to a simplified model better suited for implementing different advanced control strategies of the process in order to improve the wastewater treatment system efficiency.

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