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NONLINEAR MODELLING OF ACTIVATED SLUDGE PROCESS

A computer simulation model for the Activated Sludge Process (ASP) of a wastewater treatment plant (WWT) is presented in this paper. The model is based on non-linear equations, which depend on wastewater concentration and flow, which values vary with time. The proposed ASM1R3 model is a reduced version of the common ASM1 model due to the fact it involves only three state variables: Ss –the dissolved biodegradable organic substrate, SNO – the dissolved nitrate nitrogen and SNH – the dissolved ammonia nitrogen. In an experimental verification the model was considered as well fitted to empirical data. The proposed model is characterized by relatively low computational complexity and can be successfully applied as integral part of the overriding control systems of the WWT plant. As a result of conducted studies it was found that it is possible to apply the ASM1R3 model to optimize and improve the WWT process parameters of the regarded plant.

KEYWORDS: nonlinear modeling, wastewater treatment, Activated Sludge Process, oxygen control

1. INTRODUCTION

In recent years, Poland has been modernizing wastewater treatment plants on a large scale, replacing old and worn-out equipment with modern, characterized by high energy efficiency. Also the outdated measuring systems have been replaced with the latest generation sensors. A modern WWT plant is equipped with a control system, which monitors chosen parameters, for example concentrations of oxygen, ammonium, nitrate and phosphate, and creates predictive control strategies that enable for optimal energy savings at the facility, thus costs reduction, and improvement of the quality of treated wastewater. However, to increase the efficiency of the wastewater treatment process, particularly in terms of minimizing the operating costs, the way of interpreting signals received from the measuring devices of the control system is critical. Under normal operational conditions, the mentioned parameter values are non stationary, thus the installed control system has to react immediately in

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order to give optimum performance. The research works, results of which are presented in this paper, consider design and implementation of a non-linear, dynamic physical model which aim is to relatively quickly determine optimal values of the chosen parameters of WWT process. The adaptive-predictive model was integrated in an control system, which is installed on the considered WWT plant. By controlling of chosen WWT process parameters it is possible to reduce the operational costs of the WWT plant and to increase the effectiveness and performance of the treatment process.

The regarded physical model describes the Activated Sludge Process (ASP). This is a commonly used method for treating industrial wastewaters and sewage [2]. The organic content of the sewage in the ASP is reduced by introducing oxygen or air, combined with organisms, into it, to develop biological floc, which can be then easily separated from the clear water in a settling tank. Its advantage is a significant performance in reduction of harmful compounds. In contrast, the disadvantage is the high operating costs, which is associated mainly with the need to supply electrical energy for the blower, which introduce a suitable amount of oxygen to the wastewater. Application of optimization methods in the automatic control process may reduce the demand for electric energy, water and chemicals. The most crucial parameter, which is necessary to be regulated in the ASP is the oxygen concentration in the bio reactor. Oxygen is consumed by microorganisms and its reduction must be compensated by aeration in the WWT reactor. There exist a number of different models and methods, which are applied for ASP simulation in order to perform research studies on biological processes in hypothetical systems. Some of them use chemical oxygen demand (COD) to define the organic fraction of sewage; others use biological oxygen demand (BOD) or total organic carbon (TOC). A detailed review and comparison of different stationary and dynamic models are presented in [7, 11, 17].

The model presented in this study is based on the Activated Sludge Model no.1 (ASM1), which was designed in 1987 as the first bio kinetic model of activated sludge. The ASM1 model is currently widely applied in design of physical models. For example, in [13] authors analyze modification of the ASM1 model with respect to the International Water Association (IWA). They particularly focus on the model of the secondary clarifier, which was adopted as reactive. Their approach allows for changing the concentration value of each component in the ASM1 model before recirculation. Another method reflects to microorganisms' activity retention in the biological WWT plants, which is described in simulations by the speed test parameter, that measures the oxygen consumption by the biomass in the oxygenated sludge. An example of ASP modeling, which includes analyzes of the course of oxygenated sludge parameter is presented in e.g. [1], where the oxygenated sludge responses in four different industrial WWT plants, placed in Turkey, were modeled. Other examples of ASP models and detailed reviews an interested reader may find in e.g. [6, 8, 12, 18, 19]. For further examples Author refers also to works presented in e.g. [2, 3, 5, 9, 15, 16].

In order to achieve meaningful results, an appropriate method for model calibration must be carefully selected. The issue of ASM model calibration is undertaken in a number of publications. Significant works have been performed by [14], who proposed a schematic calibration procedure. Another example of an ASM calibration procedures can be found in e.g. [10], where a model of WWT plant, placed in Zgierz (Poland) was created using the BioWIN environment. The main difficulty with calibration of full ASM models is related to practical issues. As it will be shown below, the amount of wastewater at times changes very rapidly. Thus, under real operational conditions, the calibration procedure should be performed relatively fast. The significant contribution of the proposed ASM1R3 model lies in its low computational complexity as compared with the full model, and through this, it can be successfully applied for on-line optimization of the WWT process.

In this paper a detailed description of the designed reduced ASM1R3 model is presented.

2. A SIMULATION MODEL OF THE ACTIVATED SLUDGE PROCESS

In the study a simplified model, reflecting the behavior of the WWT plant that is placed in Kędzierzyn-Koźle, Poland, has been developed. It is a mechanical-biological treatment plant, which occupies an area of approx. 8.2 ha. It was designed for daily average flows of 16 000 m^3/d and a daily maximum of 20 000 m^3/d. The installed equipment has been dimensioned for a BOD5 load of 4000 kg O_2/d. This is an equivalent to 67 000 PE. The WWT plant is running a five-step Bardenpho system. This system has five reactors: two anoxic, two oxygen and one anaerobic reactor. There exists a recirculation between the first anoxic and aerobic reactors. The second reactor allows additional anaerobic denitrification of nitrate, which are produced by the processes of nitrification in the aerobic reactor. This process involves conversion of nitrates as electron acceptors with the carbon content. The second aerobic reactor, linked by secondary sedimentation tank, allows the reduction of nitrogen from wastewater provided to the separator. In addition, it limits the release of phosphor in the secondary settler tank.

The dynamic ASM1R3 model assumes time variable flow and concentration of wastewater in the influent and a constant concentration of oxygen in the reactors. The simplification is based on the use of an ideal model of settling tank and on the reduction of the number of state variables involved in the equations, from 13 to 3 (S_S, S_{NO} and S_{NH}), according to the original ASM1 model. The considered biological block of the WWT plant consists of five reactors and of three secondary settling tanks. The simplified simulation model reflects all five reactors and one settler as non-reactive separator. A simplified diagram of the WWT plant model is presented in Fig. 1. The variables V_1, V_2, V_3, V_4, V_5 are volumes of the particular reactors. The variables S_{O1}, S_{O2}, S_{O3}, S_{O4}, S_{O5} stay for the oxygen concentrations in the five reactors.

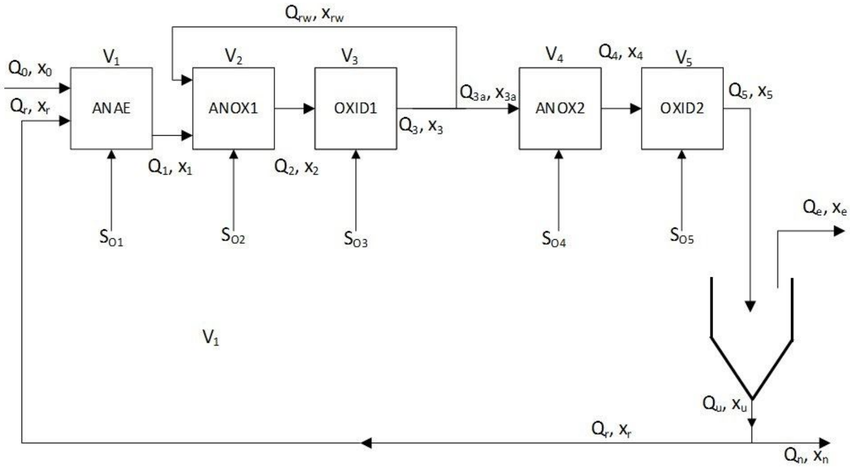

Fig. 1. The simplified diagram of wastewater treatment plant model

The influent flow Q_0 is a function of time. For this research purposes the excessive sediment Q_n was equal to zero and the influent flow was equal to the outflow Q_e. The concentration of influent wastewater x_0 was determined based on measurement of the chemical oxygen demand (COD) and the total nitrogen. The concentration x_0 changes with time and depends on three variables: S_s soluble biodegradable organic substrate, S_{NO} soluble nitrate nitrogen and S_{NH} soluble ammonia nitrogen.

The simplified model is based on works performed by [15]. The model assumes that concentrations of carbon and nitrogen substrates are dynamic and change in time. All equations that describe slowly varying processes from the full biological model are omitted. In the considered case, the dissolved oxygen concentration S_O is regulated by the main controller, installed in the WWT plant, and thus this value is constant in the ASM1R3 model. In the suspended solids X_S, fixed concentrations of easy biodegradable organic compounds are included. There are three state variables in the reduced ASM1R3 model: S_s - dissolved biodegradable organic substrate, S_{NO} - dissolved nitrate nitrogen and S_{NH}- dissolved ammonia nitrogen. The simplified Petersen matrix presenting dynamic processes involved in the model is given in Table 1.

Table 1. Matrix of the reduced ASM1R model (simplified Petersen matrix)

State variable Dynamic Process	S_S	S_{NO}	S_{NH}	Reaction no
Aerobic growth of heterotrophic bacteria	$-\frac{1}{Y_H}$		$-i_{XB}$	P_1
Anoxic growth of heterotrophic bacteria	$-\frac{1}{Y_H}$	$-\frac{1-Y_H}{2.86Y_H}$	$-i_{XB}$	P_2
Aerobic growth of autotrophic bacteria		$\frac{1}{Y_A}$	$-i_{XB}-\frac{1}{Y_A}$	P_3
Hydrolysis of organic compounds	1			P_4

Four reactions are integrated (Table 2) in the reduced model. Three of them P_1, P_2 and P_3 concern Monod kinetics and the fourth P_4 is a hydrolysis reaction.

Table 2. Reaction coefficients in the reduced ASM1R model and their description

Reaction no	Reaction coefficient [ML/T]	Reaction description
P_1	$\mu_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_{BH}$	Heterotrophic biomass growth under aerobic conditions
P_2	$\mu_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{OH}}{K_{OH}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{BH}$	Heterotrophic biomass growth under anoxic conditions
P_3	$\mu_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{OA}+S_O}\right)X_{BA}$	Autotrophic biomass growth under aerobic conditions
P_4	$k_h\frac{\frac{X_S}{X_{BH}}}{K_X+\left(\frac{X_S}{X_{BH}}\right)}\cdot\frac{S_O}{K_{OH}+S_O}+\eta_h\frac{K_{OH}}{K_{OH}+S_O}\cdot\frac{S_{NO}}{K_{NO}+S_{NO}}\cdot X_{BH}$	Hydrolysis of organic compounds

The P_1 reaction represents the aerobic growth of heterotrophs. This process is connected with the alkalinity change and gives the main contribution to production of new biomass and removal of COD. For the growth of heterotrophic bacteria a fraction of easy biodegradable substrate is used, what gives rise to an associated oxygen demand. The P_2 reaction concerns the anoxic growth of heterotrophs and nitrogen gas (denitrification). In this process the heterotrophic organisms are capable of using nitrate as the terminal electron acceptor with S_S as substrate; the nitrate is then reduced what causes alkalinity change. The alkalinity change is due to the ammonia, which serves as nitrogen source for cell synthesis. The P_3 reaction enables simulation of the aerobic growth of autotrophs (nitrification) i.e. the oxidation of ammonia to nitrate causing oxygen demand. This reaction has a significant influence on alkalinity and the COD. The P_4 reaction reflects the hydrolysis of organic compounds and, in particular, the organic nitrogen, which is broken down to soluble organic nitrogen at a rate defined by the factor η_h.

3. CALIBRATION OF THE REDUCED MODEL AND SIMULATION RESULTS

The calibration of the reduced simulation model was performed using a genetic algorithm. The objective function OF (1) was sum of norms over residuals between measured and numerically calculated values.

$$OF = norm(S^3_{NH} - y^H) + norm(S^3_{NO} - y^O) \tag{1}$$

where: S^3_{NH} and S^3_{NO} are the nitrate and ammonium nitrogen measured in the OXID1 reactor, y^H and y^O are appropriate data vectors achieved from simulations. The norm is defined as given in (2).

$$norm(A) = \sqrt{\sum_{i=1}^{N} A_i^2} \tag{2}$$

The calibration procedure regarded eight parameters. The genetic algorithm applied 50 generations. The population size was equal to 100. Adaptive mutation was used. The estimated, optimized parameter values are summarized in Table 3.

Table 3. Results of calibration procedure - parameters used in following smulations within the ASM1R3 model

Parameter name	b_H	Y_A	μ_H	K_S	K_{OH}	η_g	Y_H	μ_A
Value after calibration	0.15	0.059	4.62	54.9	0.32	0.49	0.15	1.92

Simulation result depicting calculated and measured in reactor OXID1 nitrate and ammonium nitrogen values are presented in Fig. 2.

The calibrated model gives more accurate fit between experimental and simulated data. For nitrate nitrogen, the determination coefficient $R^2 = 0.77$ and the standard deviation over residuals $\sigma = 1.0$. For ammonium nitrogen, the determination coefficient $R^2 = 0.79$ and the standard deviation over residuals $\sigma = 1.9$.

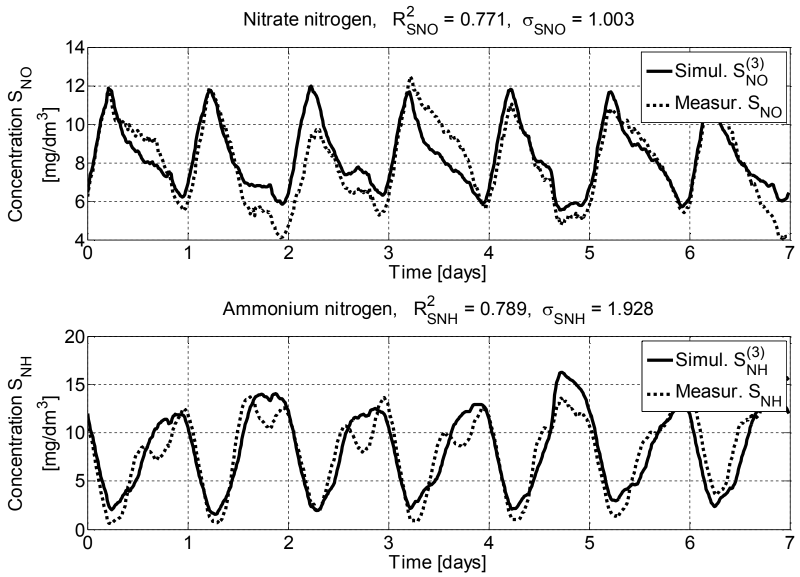

Fig. 2. Simulation results of nitrate and amonium nitrogen concentrations in the reactor no 3 (OXID1) together with the conrresponding measurement data; after the calibration procedure

Timeruns of particular state variables simulated in the reduced model are presented for all five reactors: in Fig. 3 – concentration of readily biodegradable organic substrate, Fig. 4 – concentration of ammonium nitrogen, Fig. 5 – concentration of nitrate nitrogen.

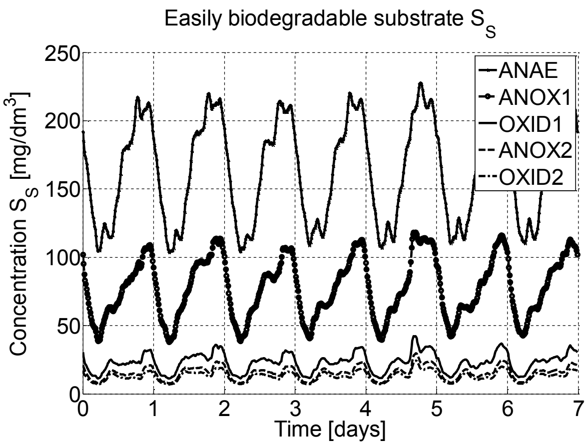

Fig. 3. Timeruns of readily biodegradable substrate concentration in the particular reactors; S_S data gathered from simulations of the calibrated ASM1R3 model

The course of organic substrate indicates that it is reduced in the particular reactors. In the first reactor the value was maximal and equaled 170 mg/dm^3. In the last reactor this value was less than 10 mg/dm^3.

The concentration of ammonium nitrogen (Fig. 4) also decreases in the consecutive reactors.

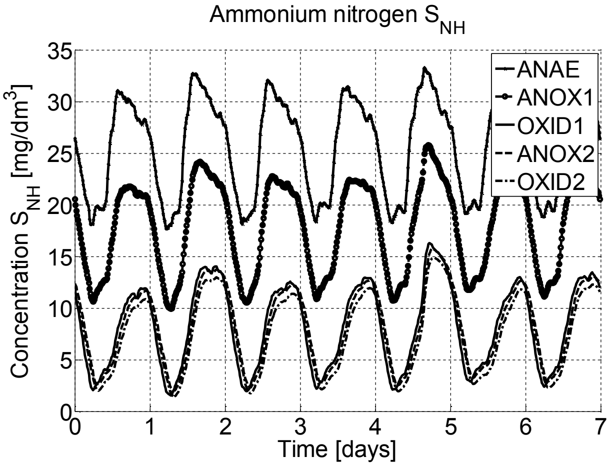

Fig. 4. Timeruns of amonium nitrogen concentration in the particular reactors; S_{NH} data gathered from simulations of the calibrated ASM1R3 model

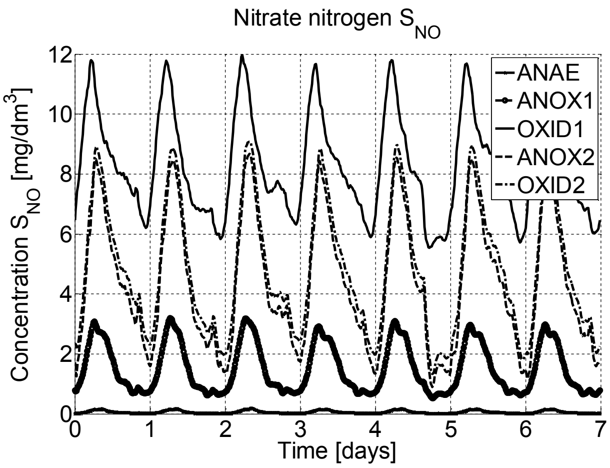

Fig. 5. Timeruns of nitrate nitrogen concentration in the particular reactors; S_{NO} data gathered from simulations of the calibrated ASM1R3 model

Decrease of ammonia causes growth of nitrate. In each of the subsequent reactor the value of nitrate nitrogen is higher.

4. CONCLUSION

The main practical aim of the performed research tasks was to expand and improve the overriding control system applied in the considered WWT plant. The overriding system provides measurement data, which are analyzed in order to allow the determination of the nature of changes, dependencies, trends and other observations of the parameter values connected with the wastewater treatment process. Simulation studies enable to determine the effect of oxygen concentration in the reactors on the reduction of ammonium nitrogen. From the point of view of optimizing the energy consumption, it is important to limit the amount of aeration, which affects the level of oxygen in the biological block. Predictive aeration systems, which are based on data, obtained directly from the model, are now the most modern way of reducing energy costs in a WWT plant. The presented ASM1R3 model enables for efficient process control in wastewater aeration while maintaining constant performance at an optimal level. Due to its implementation it is characterized by low computational complexity.

The ecological effect of presented works is associated with changes that occur in the WWT process in terms of positive impact on the protection of air, land and water. In particular, it is estimated to reduce pressure on the natural aquatic environment and the earth by not or inadequately treated wastewater in a situation, where the designed model will be used in the planning and construction of an entirely new WWT plant or in the case of modernization of existing facility. In addition, it is estimated to reduce emissions of carbon dioxide into the atmosphere by reducing the demand for electricity used in the aeration process inside the bioreactor. Application of adaptive-predictive overriding control system for WWT process with integrated ASM1R2 model, described in this paper, creates opportunity to reduce the operating costs even by 10% to 40%. The costs associated with the implementation of systems, which are using optimization methods will reimburse in few years and in some cases within a few months.

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