ISSN 1392 – 124X INFORMACINĖS TECHNOLOGIJOS IR VALDYMAS, 2004, Nr. 3(32)

PROCESS SIMULATOR FOR WASTEWATER TREATMENT PLANT

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Abstract. Dynamic models and process simulators can be very useful in creation of effective control systems for wastewater treatment processes. They also allow seizing procedures of designing of technological processes, helping to estimate and to pick up successfully technological parameters, which influence stability and efficiency of processes. Modern wastewater treatment is a quite complex process, which includes several treatment steps before the water is released to the recipient. The typical process of wastewater treatment includes four stages: mechanical treatment, biological treatment, chemical treatment, and sludge treatment. In this paper the separate models for each wastewater treatment stage are combined to form a complex dynamic model for simulation of wastewater treatment plant. Important data from Kaunas wastewater treatment plant are collected to facilitate the identification of mathematical models parameters.

Key words. Wastewater, biological treatment, modelling, simulator.

1. Indroduction

Modern wastewater treatment is a fairly complex process, which includes several treatment steps before the water is released to the recipient. A very typical strategy is to have four different process steps, [1], [4] (see also Figure 1):

- mechanical treatment,
- biological treatment,
- chemical treatment,
- sludge treatment.

In the first step, the mechanical treatment, larger objects are collected on a grid and heavy particles like sand are trapped in a sand trap. Also, the mechanical treatment step often includes a primary sedimentation where particles are allowed to settle.

The second treatment step is the biological treatment, and we analyse one version of this biological treatment. There exist several different biological processes for wastewater treatment, but the most common one is the activated sludge process [2]. In the activated sludge process, different microorganisms decompose organic matter. It is also possible to extend the activated sludge process for nitrogen removal. The biological treatment step also includes a settling tank, where microorganisms and particulate matter can settle. The sludge that accumulates on the bottom of the settling tank are partly removed, and partly recirculated back into the process in order to keep the concentration of microorganisms in the water on a sufficiently high level.

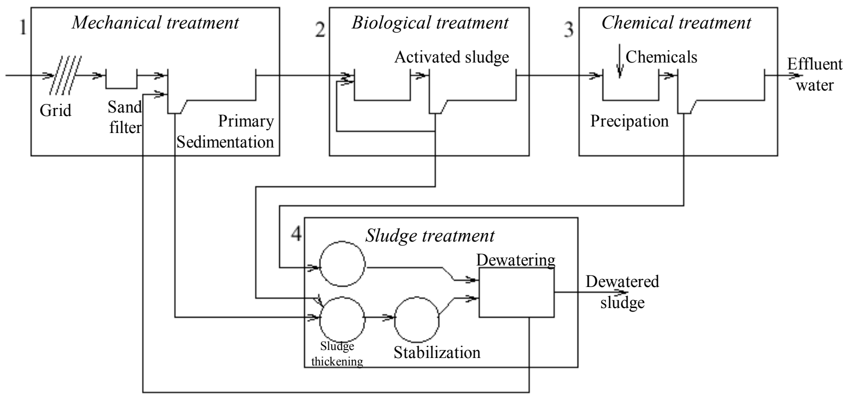

Figure 1. Typical layout of a wastewater treatment plant

The most common purpose with the chemical treatment step is to remove phosphorus. Adding precipitation chemicals to the wastewater does this. These chemicals will convert the solved phosphorus into insoluble compounds and also stimulate flocculation. The flocks may then be removed either by sedimentation or by flotation. Another possible chemical treatment is to remove pathogens by chlorinating the water.

Sludge from the three steps described above is fed to the sludge treatment. The sludge that is removed from the different process blocks is digested to reduce odour, to give methane gas and to kill potential pathogens. This can be done in an anaerobic digester, where the high temperature kills most microorganisms, and organic matter is degraded.

2. Description of Kaunas Municipal Wastewater Treatment Plant

A new mechanical-chemical wastewater treatment plant (WWTP) was commissioned in September 1999. The full facility including the sludge digestion, dewatering and biogas system was commissioned in June 2000.

All municipal wastewater treatment processes are presented in Figure 2 [10]. The biological treatment step is on the designing phase in Kaunas WWTP now.

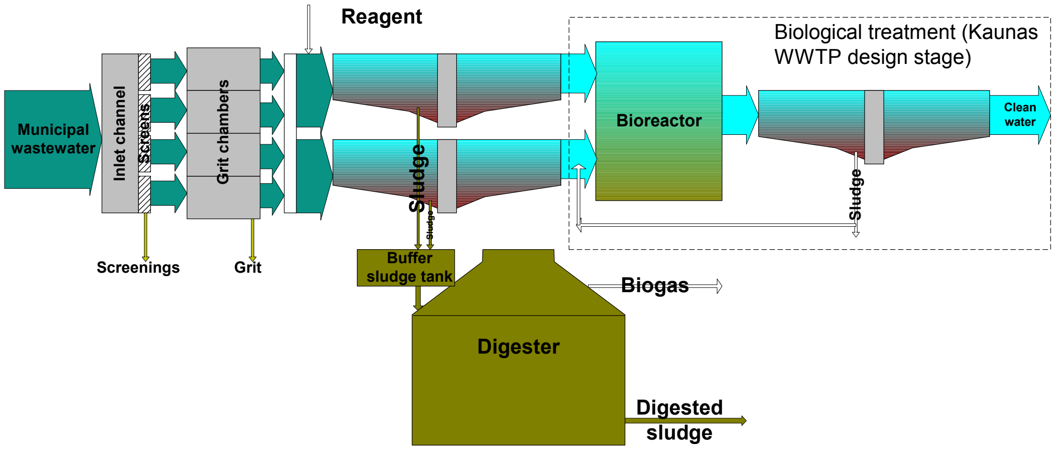

Figure 2. Kaunas (Lithuania) wastewater treatment plant

Municipal wastewater arrives in to inlet channel (400m³ volume). From the inlet channel wastewater pass through four screens to four grit chambers (520m³ volume each). The screens filter different screenings (near 7% solids from wastewater). In the grit chambers sand is removed (near 6.5% solids from wastewater). Further the wastewater accesses the primary settlers. Kaunas WWTP has four sedimentation tanks (7260m³ volume each, and 2200m² sedimentation square each), but only two are used. Together with the water to the settlers reagent is supplied, which accelerates the settling process. In the future, the reagent will not be used, because it is expensive and is not useful for biological treatment. The settler is an important part of the wastewater treatment process. It is used for two purposes: clarification and thickening. In a settler, particulate matters sink to the bottom of the settler (thickening), and clear water is produced (clarification) and removed from the top of the settler. The particulate matter at the bottom of the settler (the sludge) contains necessary materials for biogas producing during digestion process. The removed sludge from the bottom of the sedimentation tank is transported first to buffer sludge tank (150m³ volume) and further to two digesters (9000m³ volume each).

Kaunas WWTP produces biogas in digesters, where sludge is digesting [10]. Duration of digestion is 20-22 days, temperature 34-36°C. Produced amount of sludge by dry materials is 16.24t/day (organic materials – 11.4 t/day). Fragmentation degree of organic materials is 52%. So, amount of fragmented organic materials is $11{,}4 \times 0{,}52 = 5{,}928$ t/day. Theoretically, 1,4-1,7m³ biogas (5958 × (1.4 ÷ 1.7) = 8299.2 ÷ 10776 m^3/day) can be produced from 1kg fragmented organically materials. But in practice the produced biogas amount is 8000-10000m³/day in Kaunas WWTP.

Biogas is a gas mix, produced by metanogeno bacteria, which are utilizing biomaterials under anaerobic conditions. Biogas compounds from 50-70% methane (CH_4), 30-40% (CO_2), nitrogen, hydrogen sulphide, and water steam [7]. The amount of the produced methane depends on sludge kind and on particulate materials concentration. Metanogeno bacteria is activating organic materials for fermentation and activating discharge of biogas. Bacteria are slowly growing and are very sensitive to microclimate changes, physical and chemical conditions. The quality of biogas production is affected by environment pH (alkalinity), temperature, sludge's feeding rate, age of sludge, etc. Temperature is main of those factors. Metanogeno is passive in extremely high or extremely low temperature. So, especial attention is pointed to stabilization of temperature. Biogas can be transformed into mechanical or thermal energy.

Different biological treatment processes exist, but mostly wastewater treatment plants make use of the activated sludge process [3], [5], [6]. This type of biological treatment process will be implemented at Kaunas WWTP. In its basic configuration the activated sludge process consists of an aerated tank and a settler. The microorganisms grow slowly in the aerated tank. In order to maintain their population sizes, sludge that contains microorganisms from the secondary settler is recirculated back to the aerated tank. Excess sludge is removed to both avoid sludge in effluent water and to maintain a reasonable concentration of suspended solids.

3. Mathematical model

The dynamic models are valuable tools for the plant operator or the designer in forecasting or explaining the performance of the wastewater treatment plant. They also can help to evaluate the efficiency of different process control strategies. The mathematical models on the basis of material balances are created for each (inlet channel, grit chambers, sedimentation tank, digester, buffer sludge tank, bioreactor) wastewater treatment process. The mathematical models are not presented in this paper because they were already analysed in earlier papers. The details about these models are presented in:

- the mathematical model for the processes in inlet channel, grit chambers, buffer sludge tank widely is analysed in paper [10];
- the mathematical model for the processes in sedimentation tank widely is analysed in paper [11];
- the mathematical model for the processes in digester widely is analysed in paper [7];
- the bioreactor and the secondary settler models are, however, not identified in the real plant (because the biological treatment part for Kaunas WWTP is only in designing stage now). Therefore the hypothetical values of technological parameters and model parameters are used here. Also we used the same mathematical model parameters for the mathematical model of the secondary sedimentation as for primary sedimentation. The dynamic of activated sludge process was particularly analysed in [8], [9].

4. Realization of the mathematical model

The different mathematical models were combined to complex mathematical model of the Kaunas wastewater treatment plant (prospective biological treatment section is included). The programming package 'Simulink' (Matlab) was used for realizing of the complex mathematical model (Figure 3).

The model reactions to different process interferences were analyzed. The most important interferences are:

- disturbances of readily biodegradable substrate concentration (S_S) in influent water;
- disturbances of influent water flow (Q).

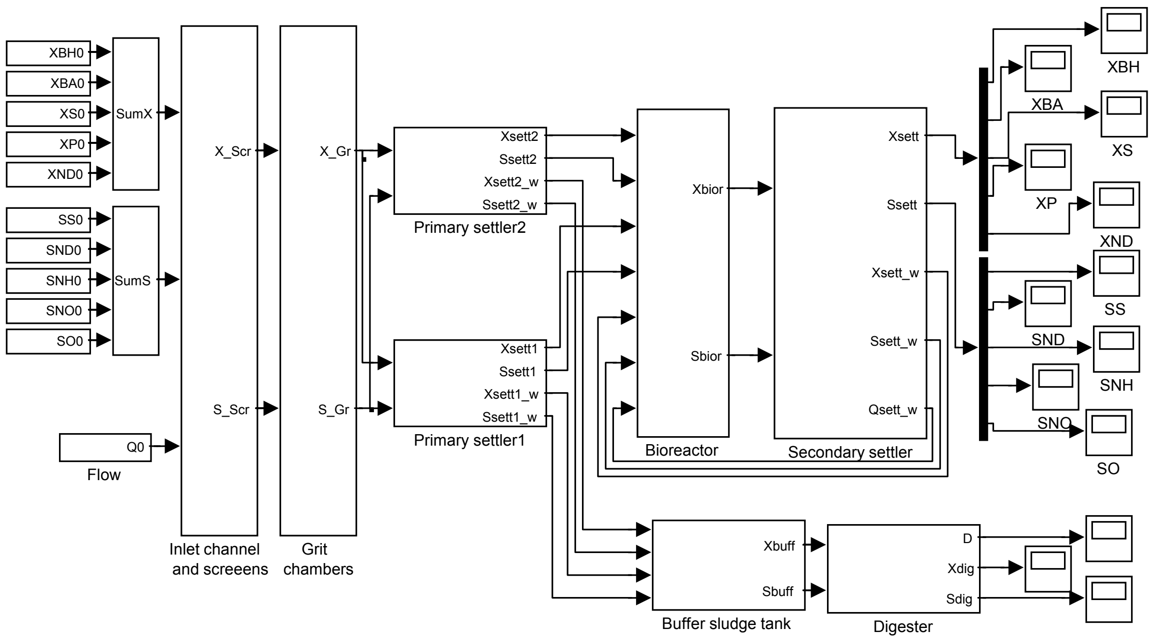

Figure 3. Realization of mathematical model in Matlab/ Simulink environment

The composition of influent wastewater is presented in Table 1.

Table 1. Composition of influent wastewater [10]. The values approximately correspond to the composition of pre sediment wastewater at the main municipal plant in Kaunas. The influent water flow is 3000m³/h.

Standard abbreviation	Variable	Concentration (mg/l)
$X_{B,H}(t)$	Heterotrophic biomass	0
$X_{B,A}(t)$	Autotrophic biomass	0
$S_S(t)$	Readily biodegradable substrate	80
$X_S(t)$	Slowly biodegradable substrate	414.3
$X_P(t)$	Particulate inert organic matter	217.2
$X_{ND}(t)$	Particulate biodegradable organic nitrogen	29.3
$S_{ND}(t)$	Soluble biodegradable organic nitrogen	2.1
$S_{NH}(t)$	NH_4-NH_3 nitrogen	23.5
$S_{NO}(t)$	Nitrate and nitrite nitrogen	1
$S_O(t)$	Dissolved oxygen	0.1

First of all the designed bioreactor (volume is 23500m³) was simulated under aerobic conditions (without the recirculation).

Reaction curves of the WWTP state variables are presented in Figures 4a,b. The process reaction on different disturbances was as follows:

- readily biodegradable substrate concentration (S_{S1}) in influent water is changed from 80 to 104mg/l in step disturbance (fine curve);
- influent water flow (Q) is changed from 3000 to 4100m³/h in step disturbance (bold curve).

In Figure 4a the values of heterotrophic biomass ($X_{B,H}$), autotrophic biomass ($X_{B,A}$), readily biodegradable substrate (S_S), slowly biodegradable substrate (X_S), particulate inert organic matter (X_P) are presented. In Figure 4b the values of particulate biodegradable organic nitrogen (X_{ND}), soluble biodegradable organic nitrogen (S_{ND}), NH4-NH3 nitrogen (S_{NH}), nitrate and nitrite nitrogen (S_{NO}), dissolved oxygen (S_O) are presented.

The designed bioreactor (10 cameras, total volume is 23500m³) was simulated under anaerobic (first 6 cameras) and aerobic (4 cameras) conditions with recirculation from last to first camera and from sedimentation tank to first camera, in the second step.

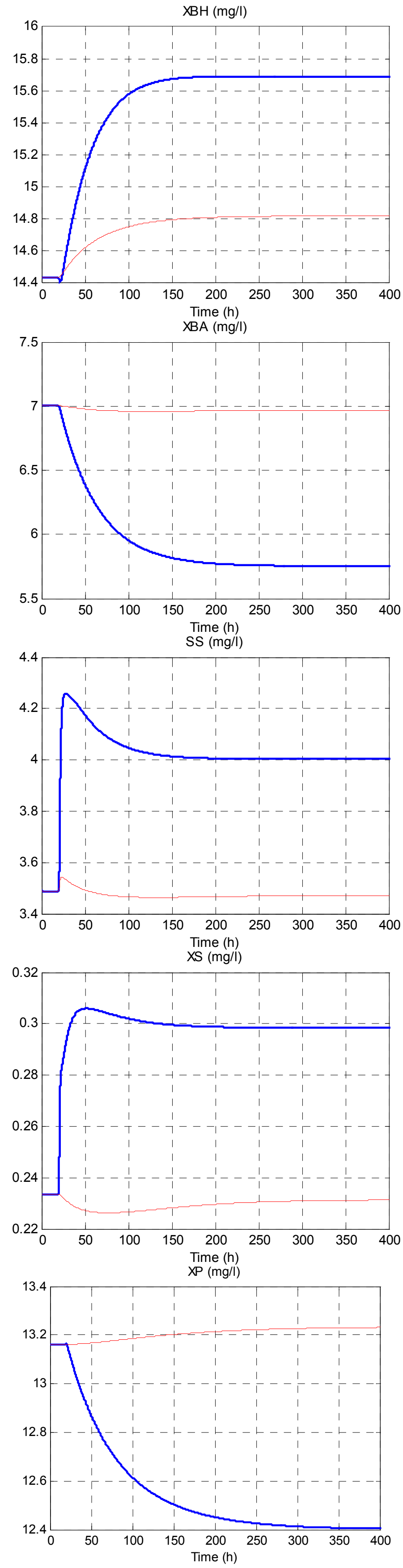

Figure 4a. The process reaction on typical process disturbances (meanings of symbols are presented in text)

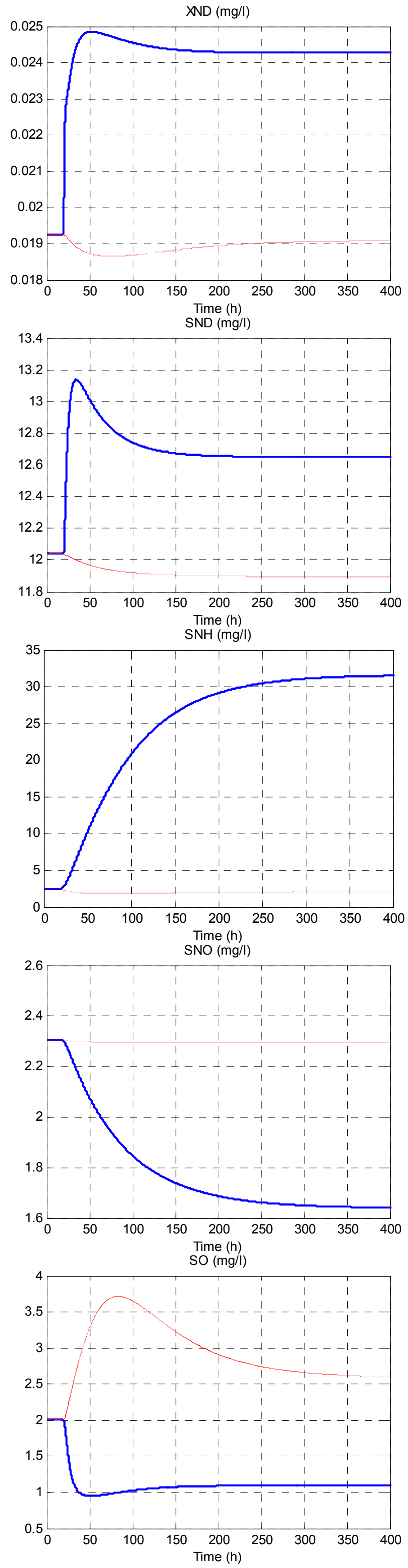

Figure 4b. The process reaction on typical process disturbances (meanings of symbols are presented in text). The designed bioreactor was simulated under aerobic conditions (without the recirculation)

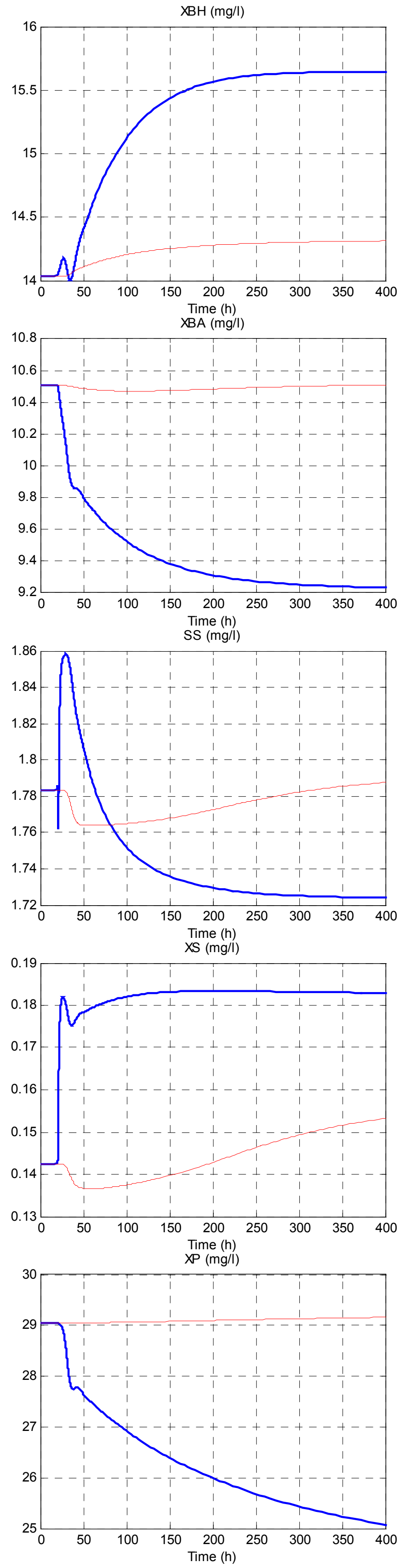

Figure 5a. The process reaction on typical process disturbances (meanings of symbols are presented in text). The designed bioreactor (10 cameras) was simulated under anaerobic and aerobic conditions with recirculation from last to first camera and from sedimentation tank to first camera

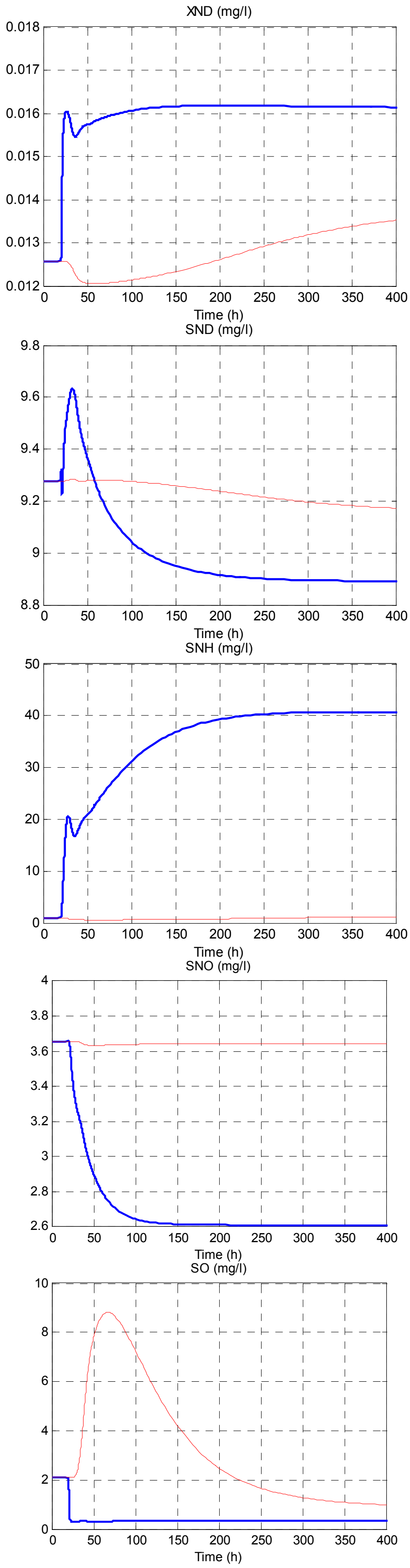

Figure 5b. The process reaction on typical process disturbances (meanings of symbols are presented in text). The designed bioreactor (10 cameras) was simulated under anaerobic and aerobic conditions with recirculation from last to first camera and from sedimentation tank to first camera

Reaction curves of the WWTP state variables are presented in Figures 5a,b. The process reaction on different disturbances was as follows:

- readily biodegradable substrate concentration (S_{S1}) in influent water is changed from 80 to 104mg/l in step disturbance (fine curve);
- influent water flow (Q) is changed from 3000 to 4100m³/h in step disturbance (bold curve).

In Figure 5a the values of heterotrophic biomass ($X_{B,H}$), autotrophic biomass ($X_{B,A}$), readily biodegradable substrate (S_S), slowly biodegradable substrate (X_S), particulate inert organic matter (X_P) are presented. In Figure 5b the values of particulate biodegradable organic nitrogen (X_{ND}), soluble biodegradable organic nitrogen (S_{ND}), NH4-NH3 nitrogen (S_{NH}), nitrate and nitrite nitrogen (S_{NO}), dissolved oxygen (S_O) are presented.

The modeling results clearly show the complex relationship between different variables of wastewater treatment processes. These results could be very useful for designing and tuning of effective control systems for all wastewater treatment processes already now. However, it is very important to prove accuracy of the biological treatment model, based on the data obtained from industrial wastewater treatment plants. This will be done in further studies.

The designed bioreactor was simulated under aerobic conditions (without the recirculation).

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DOI: 10.5755/j01.itc.32.3.11863