The mathematical modeling and monitoring for process of a biological sewage treatment

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Abstract. The urgency of present problem is caused by necessity of operative control of biological sewage treatment processes. At present these processes are realizing in aeration tanks of sewage treatment plants both municipal and of large enterprises. A process of biological treatment is being checked by chemical analysis practically by hand. By the way a duration of checking procedure is commensurable with the time the sewage water is passing through an aeration tank. Thus any operative control of sewage treatment is practically impossible. In the present work it is proposed to use for operative control the hardware-software complex (HSC) AQUATEST-AT4M, that is able to produce an analysis of water quality in some minutes. By the way the measurement data give an opportunity to identify a mathematical model of these biological sewage treatment. In this work there are presented the results of experiments and of mathematical modelling of work of the Kirov City communal systems sewage treatment plants (KCS STP).

1. Introduction
The aim of present research is to substantiate the possibility of operative control of sewage treatment quality in aeration tanks of sewage treatment plants. At present we can observe two intercommunicated tendencies: a rising number of modern scientific researches, aiming on development of various water treatment methods – on one hand, and steady deterioration of water quality, on the other hand. In perspective plan three main problems are most valuable for the drinking water supply of the Russian populated areas, except of the intensification of water resources protection from pollution: the modernization of water treatment technologies and of water distribution networks, revision of scientific concepts of drinking water supply, improving of monitoring of the drinking water quality and of the legal basis in the water-economy sphere. Monitoring of environmental conditions (and water resources first of all) is carried out at present by using of the colorimetrics, titrometrics, chromatographical methods and other more sophisticated ones. Some of those possess quite adequate informatively but they are as a rule expensive, time- and labour-consuming and not responding to automation. The serious fault is that these methods demand preliminary sample preparations and using of high toxic chemicals, therefore working takes place mainly in laboratories. For rising of efficiency there are developed express methods of chemical analysis – test-systems based on visual-colorimetrics and spectrum-photometrics methods [1]. These methods are of relative low sensitivity and cannot be used for rigid automotive environmental monitoring as well. Many of given ways of
investigation allow to measure one or restricted number of water composition indices that is in principle insufficient for monitoring in real time scale. This work presents the hardware-software complex AQUATEST-AT4M destined for operative control of water quality and developed by one of the authors [2].

2. Materials and methods
A method of taking up samples along all length of an aeration tank by equal intervals is used for estimating quality composition of wastewater in tanks of STP KCS. Taking samples of the same quantity is made along all length of a tank divided by eight equal intervals. A receiver with seven pipework’s is used for sampling. Taken water samples are poured down into marked canisters. Then the samples are diluted by distillate to a concentration necessary for precision of measurement and are going to input of HSC AQUATEST-AT4M to be subjected to cyclic oxidization reactions. Basing on reviewing available information concerning the STP KCS function and given data of previous investigations the main measurement objects was selected, namely pollutant concentrations of nitrogen group (ammonia-ion, nitrite-ion, nitrate-ion) and chemical oxygen demand index (COD) [3-6].

![Figure 1. Oxidation curve, notch 0 m.](image1)

![Figure 2. Oxidation curve, notch 54 m.](image2)

![Figure 3. Oxidation curve, notch 108 m.](image3)

![Figure 4. COD index distribution along first passage of aeration tank.](image4)

Software of the complex is implemented in common configuration of a personal computer and carries out both pretreatment of physical-chemical analysis data and transformation, storage, output and visualization of digital information in the convenient and available form, for instance in the
electronic table MS Excel. Besides standard facilities of Excel the HSC allows to use its own inner convenient interface for control, setting and output of visual information taken by measurements. Figures 1 - 4 show the instances of visualization of COD measurement data along an aeration tank of the STP KCS. Total length of a passage of the aeration tank is 216 m. The samples were taken up on 06.02.2015. Presented plots define the COD index as an integral value. Here the vertical axis represents intensity of oxidability, $mgO_2/dm^3$, horizontal axis is time, sec.

3. Results
The is suggested a mathematical model for description of biological sewage treatment process which considers dynamics of concentrations of nitrogen substrate and micro biota of two species [7-11].

Nitrogen is removed from wastewater through nitrification, followed by denitrification. Nitrification is the oxidation of ammonia ions $NH_4^+$ to nitrates $NO_3^-$, being itself a two-step process. On the first step bacteria of species *Nitrosomonas* oxidize ammonia to nitrite $NO_2^-$ by the scheme

$$NH_4^+ + \frac{3}{2}O_2 \rightarrow 2H^+ + NO_2^- + H_2O$$

On the second step bacteria of species *Nitrobacter* oxidize nitrite to nitrate by the scheme

$$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^-$$

Denitrification is a process of reduction of nitrates to molecular nitrogen occurring outside aerotanks.

In [7, 12] such a model of nitrification is considered in which processes connected with nitrogen oxidation are separated of other processes of biological sewage treatment and described by equations:

$$\begin{align*}
\frac{dN_1}{dt} &= -\mu_1 \frac{N_1}{K_{N_1} + N_1} B_1 \\
\frac{dN_2}{dt} &= \mu_1 \frac{N_1}{Y_1 K_{N_1} + N_1} B_1 - \frac{\mu_2}{Y_2 K_{N_2} + N_2} B_2 \\
\frac{dN_3}{dt} &= \mu_2 \frac{N_2}{Y_2 K_{N_2} + N_2} B_2 \\
\frac{dB_1}{dt} &= \mu_1 \frac{N_1}{K_{N_1} + N_1} - k_{d_1} B_1 \\
\frac{dB_2}{dt} &= \mu_2 \frac{N_2}{K_{N_2} + N_2} - k_{d_2} B_2
\end{align*}$$

where $N_1, N_2, N_3$ — ammonia, nitrites and nitrates concentrations respectively; $B_1, \mu_1, k_{d_1}$, and $B_2, \mu_2, k_{d_2}$ — concentrations, maximum specific rates, death rates (mortality coefficients) of bacteria species *Nitrosomonas* and *Nitrobacter* respectively; $Y_1, Y_2$ — economical coefficients; $K_{N_1}, K_{N_2}$ — half-saturation constants. Initial conditions for system (1) are taken of measurement data in corresponding points of aeration tanks, fitting the parameters of the model is a separate task being considered below. To solve the system (1) one must identify simulation model using COD measurement data and direct measurements of nitrogen group concentrations along all the way the mixture of wastewaters and activated sludge passing through aeration tank. The HSC computes this index integrating the curve of oxidation defining the intensity of oxidation processes in wastewater.

It was found is a result of experiments that main pollutions in industrial effluences come in STP KCS from wastewater outlets of Kirov Biochemical Plant (BCP). The following measurement series made from 20.03.2015 to 26.03.2015 were carried out while over pollutant wastewaters were coming
from BCP. For estimating influence of BCP working it was taken up simultaneous water samples on BCP and STP KCS on 26.03.2015. There is a confrontation of these samples on Fig. 5 for analysis of their interdependency.

![Oxidation curves plot](image1)

**Figure 5.** Oxidation curves plot: above – BCP, bottom – STP KCS, notch 0 m.

![COD index distribution along first passage of aeration tank of BCP](image2)

**Figure 6.** COD index distribution along first passage of aeration tank of BCP.

By the way distribution of the COD in the first passage of aeration tank of BCP appeared as shown on figure 6. It was found during experiments that most significant index of pollutions is presented in wastewater of contaminants of nitrogen group – ammonia-ions ($\text{NH}_4^+$), which is a result of oxidizing reactions are transforming consequently in nitrite-ions ($\text{NO}_2^-$), then in nitrate-ions ($\text{NO}_3^-$).

Interdependence between COD index and ammonia concentration in standard mode of work of STP KCS is confirmed by plot of these values on figure 7.

Solving the task of identification of the equations system (1) was being done based on real identifying by next parameters: $\mu_1$, $k_{d_1}$, and $\mu_2$, $k_{d_2}$ — maximum specific rates, death rates of bacteria species Nitrosomonas and Nitrobacter respectively; $Y_1$, $Y_2$ — economical coefficients; $K_{N_1}$, $K_{N_2}$ — half-saturation constants. For fitting of model parameters a quadratic functional of deviations of experimental concentrations from calculated ones of COD and of nitrogen group was used, minimization of which allowed determining indispensably values of the parameters. The fitting of the parameters $\mu_1$, $k_{d_1}$, and $\mu_2$, $k_{d_2}$; $Y_1$, $Y_2$, $K_{N_1}$, $K_{N_1}$ was made as follows: taking the measurement data of the COD along all length of aeration tank (Fig. 4) parameters $\mu_1$, $k_{d_1}$ and $\mu_2$, $k_{d_2}$ were established. Parameters $\mu_1$, $k_{d_1}$, and $\mu_2$, $k_{d_2}$ were invariable for all versions $\mu_1=0.424$, $k_{d_1}=0.01$, $\mu_2=0.173$, $k_{d_2}=0.01$. Taking the measurement data of the nitrogen group parameters $K_{N_1}$, $K_{N_2}$ and $Y_1$, $Y_2$ were identified. The identification procedure is considered on a sample of nitrogen group. According to measurement data (figure 7):

$$N_i(t_k): i=1,...,m; \quad k=1,...,p; \quad t_k = \tau_{i,m} + \tau_{i,m}^p; \quad (m=3,p=7); \quad \tau = \{0.0,0.125,0.25,0.375,0.5,0.75,1\}^7;$$

as $N_i(t_k)$ are of different order, weight coefficients $W_i$ are introduced so that mean values of $N_i(t_k)$ were of the same order. Dimensionless values are introduced...
The target function of these arguments is built as the quadratic functional

\[ F(\xi_1, \xi_2, \xi_3, \xi_4) = \sum_{i=1}^{m} \sum_{j=1}^{p} |W_i (N_i(0) - N_i(t_i))|^2 \rightarrow \min \]  

(2)

Results of numerical experiments are presented on figure 8. Here the following data of parameters and entry conditions are used for calculation:

- \( \mu_1 = 0.424; \mu_2 = 0.173; k_{N_1} = 315.5; k_{N_2} = 5.2; Y_1 = 2.25; Y_2 = 1.35; k_{d_1} = 0.01; k_{d_2} = 0.01; t_0 = 0; t_n = 400; \)
- \( N_{1}(0) = 23.0; N_{2}(0) = 4.0; N_{3}(0) = 0.0; B_{1}(0) = 0.3; B_{2}(0) = 0.6 \)

4. Discussion

One should be noted that wastewaters from sewage treatment plants of the industrial enterprises of Kirov city were relatively faintly contaminated in that time when the water samples shown in pic. 1 – 4 were taken up. The KCS STP handles with sewage treatment enough effectively and swiftly under such favourable circumstances – COD does not change just after wastewaters are passing a half of length of the aeration tank. The working regime of the STP can be modified under such conditions: the mass of activated sludge might be reduced; the output of air pumps providing mixing of wastewater in the passages of tanks might be diminished. Such actions would result in considerable savings of activated sludge and energy expense. Presented results of measurement by HSC AQUATEST-AT4M allow not only to identify and to tune a mathematical model of biological sewage treatment processes but to accomplish a full valuable monitoring of industrial wastewaters treatment by enterprises that seems to be of importance.
Figure 8. Ammonia, nitrite, nitrate, bacteria *Nitrosomonas* and *Nitrobacter* concentration distributions.

5. Conclusion
Models most exactly described the biological treatment process are multiparameter. Hence there is urgent to solve the problem of choosing a simplified model considering dynamics of main components of waste going in. In our case that is a model of nitrogen group dynamics: of ammonia, nitrites and nitrates. In most cases methods of parameter identification demand many experimental data not always available. For obtaining such data the AQUATEST-AT4M device was used which allows to get and to treat swiftly experimental data following suggested procedures. The model identification was fulfilled on the next stage based on experimental measurements. A biological sewage treatment process demands substantial financial expenses. A possibility to attribute a specific polluting agent can be realized when the monitoring procedure would be carried out systematically on wastewaters outlets of enterprises and on input of the STP KCS. Quality control of function of both enterprises and KCS STP would be realized operatively and in full measure by using the HSC in work process that would optimize expenditures of activated sludge, energy and other expenses. The tuning of the HSC for other contaminants registration is possible by using specialized sensors that can enhance monitoring quality. The software of the HSC can quite be included in an integrated informational control system of biological sewage treatment and waste monitoring processes. Influence of heavy metals on vital capacity of bacteria is evaluated in the suggested model by the scenario variations of bacteria death rates. Four scenarios are considered and it is shown in [12] that variations of these coefficients produce substantial effects on activities of the STP in the whole: rising of death rates by 30% appreciably damps effectiveness of action of activated sludge and their growth by 100% and more in fact totally cancels all work of the STP concerning the biological sewage treatment.

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