ADVANCED CONTROL OF AEROBIC INDUSTRIAL WASTEWATER TREATMENT

Matei Vinatoru, Eugen Iancu, Gabriela Canureci and Camelia Maican
University of Craiova, Automation and Mechatronics Department

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Abstract: The paper present the possibility of automatic control of the biological wastewater treatment station with applications in Romanian Chemical Companies. In this paper are developed a mathematical model for biological aeration basins and two automatic control systems (conventional control structure using three-positional controllers or PLC and advanced control structure using state estimators) for wastewater industrial purification stations.

1 INTRODUCTION

In the present world, environmental issues are a very important topic. More and more countries and international bodies are issuing stringent laws and standards for environment protection. A major field in environment protection is the industrial wastewater treatment, geared toward protecting world waters from pollution. Biological processes are the ones most used in wastewater treatment today. (Chen 2001, Peter, 2003). These processes, used to remove both inorganic and organic products, take place in wastewater treatment plants. The wastewater is treated using complex chemical and biological reactions, before being discharged in the environment. The schematic operational block diagram of such treatment plant is presented in figure 1. The residual wastewater discharged by industrial plants contains a lot of contamination substances (organic and inorganic matters, ammonium and nitric compounds), which shall be eliminated before the water is discharged in environment. Different treatment techniques are used to eliminate those substances, as physical/chemical treatment techniques and treatment by microorganisms called biological aerobe purification.

In the chemical treatment, certain chemicals are added to the wastewater. These chemicals are interacting with the contamination substances, changing there structure and allowing their elimination through mechanical processes (screen, grit, filtration). In the same time, the pH of the solution is brought to the neutral point. Most of fertilizers such as nitrates can be removed this way. Biological treatment processes are used to remove the dissolved organic load from the water using microorganisms. They use aerobic bacteria for the decay of the organic matter. Aerobic bacteria must be present, in order to perform the chemical conversion of biological contaminants in other substances that can be easily eliminated trough simple mechanical processes.

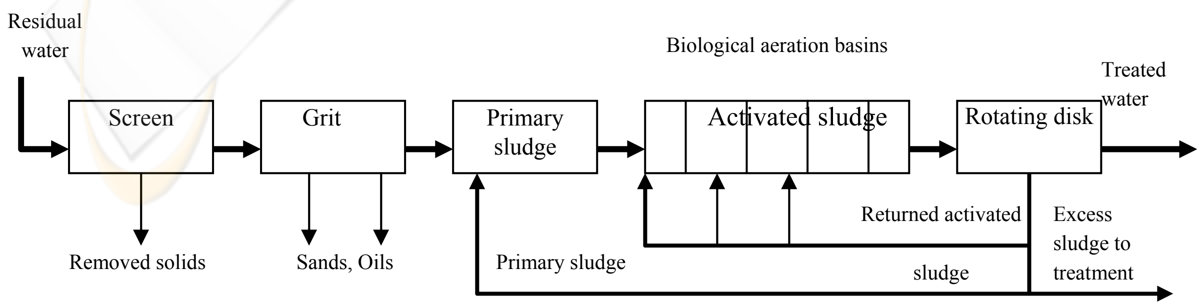

Figure 1: Wastewater industrial purification.

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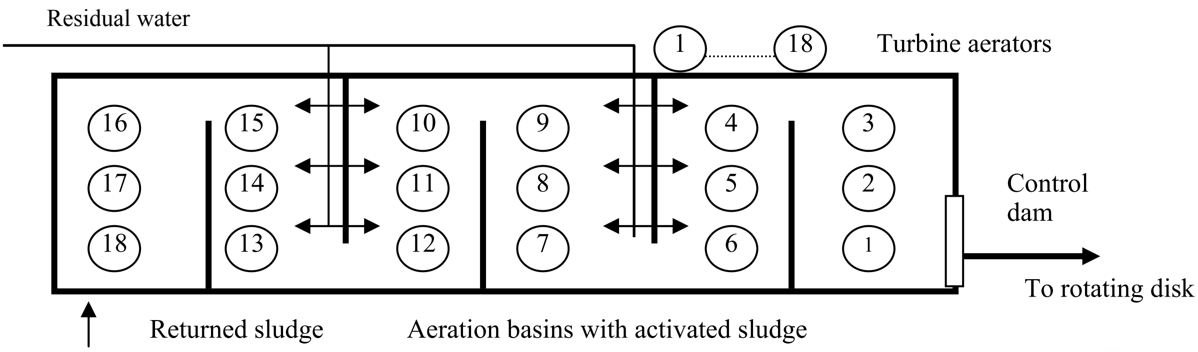

Figure 2: Aeration basins with activated sludge.

The contaminants are converted to carbon dioxide and water as a result of the following reaction.

$$\begin{bmatrix}\text{Organic}\\\text{load}\end{bmatrix}+O_2+[\text{Bacteria}]\Rightarrow CO_2+H_2O+\begin{bmatrix}\text{moore}\\\text{Bacteria}\end{bmatrix}. \quad (1)$$

In this case the Biological Oxygen Demand (BOD) defines the organic load. The biological treatment processes take place in biological aeration basins. Turbine aerators are used to aerate the water in order to maintain the optimal oxygen concentration for bacteria and also mix the water, keeping the media homogenous. The industrial wastewater and primary sludge (with bacteria) are mixed inside the aeration basins, and bacteria consume the organic matter resulting new bacteria, called activated sludge. The activated sludge exists normally in the form of flakes, which, besides live and dead biomass, contains absorbed and stored, both organic and mineral parts.

In order to control the content of the biomass, it is necessary to control the oxygen dissolved in the basin water, which can be achieved through the control of the turbine aerators (level, flow, speed, or number of running aerators). The turbine aerators inside the aeration basins can be considered as a distributed structure (see figure 2), and considering bacteria's growing and activity requirements, it is necessary to design an advanced control system to assure a high efficiency of the process (water quality, cost reduction). This paper presents an automatic control system for the biological wastewater treatment in Romanian treatment stations. The schematic diagram of the aeration basins is presented in figure 2.

It is necessary to control the aeration process of the wastewater in the biological treatment basins, in order to obtain the optimal conditions for aerobic bacteria growth and evolution (Peter, 2003). The problem of oxygen concentration measurement in solutions was already solved both in the country and abroad (Vinatoru,1979, Vanrolleghem, 2003).

The aeration process can be controlled as follows:

- through the control of the turbine immersion relative to the water level in the basin;
- through the control of transit time of wastewater in the aeration basin through the rising or lowering of the control dam;
- through the number of running aerators in each basin, which is the most efficient method for oxygen concentration control;
- through variation of the rotational speed of the aerators; this method cannot be applied in Romanian installations, since the rotational speed cannot be modified for the motors used.

2 THE MATHEMATICAL MODEL OF THE AERATION BASINS

Considering the oxygen concentration control possibilities, the aeration basins can be considered as an oriented object with three inputs (w-rotational speed of the motors driving the aerators, n-number of aerators running and h-level of water in the basin relative to the lowest position of the aerators) and one output (c-oxygen concentration in the basin). The oxygen concentration is a function of both time and spatial coordinate along the water path from the entrance in basin 6 to the exit over the dam in basin number 1.

We will consider one basin and the mathematical model for the dynamic regime is given by the following equations:

-The equation for the water flow over the dam in the aeration basin 1:

$$F_a = \alpha.b.\sqrt{2g}.(H-l)^{3/2} \text{ where } \alpha=(0,5-0,6)$$

-The equation for the aeration pump flow:

$$F_p = 738,432.\gamma.(n_s/n)^2.h^{3/2}$$

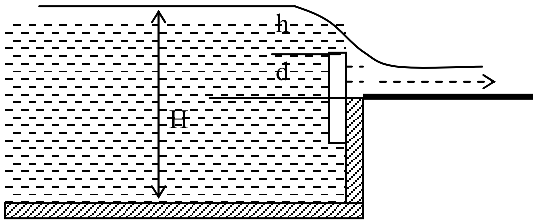

Figure 3: Dam measures.

-The quantity of oxygen used by microorganisms in the time unit and volume unit:

$$\frac{dC}{dt} = k_{au}(C_s - C) \qquad (2)$$

-The global mass balance equation can be considered stationary since the water volume V variations can be neglected inside the basins:

$$F_{i1} + F_{i2} + F_{i3} - F_e = 0 \qquad (3)$$

-The mass balance equation for the dissolved oxygen:

$$V\frac{dC_i}{dt} = F_{i1}.C_{i1} + F_{i2}.C_{i2} + F_{i3}.C_{i3} + + H_i.F_p(C_r - C_i) - F_e.C_i - k_{au}V(C_s - C_i) \qquad (4)$$

The liquid volume in the basin is given by the formula:

$$V = A\,(H_l + h)$$

For a particular case of treatment basins, the general mathematical model described by equations 1 to 6 can be linearized around the stationary values and simplified, resulting the schematic block diagram presented in figure 4.

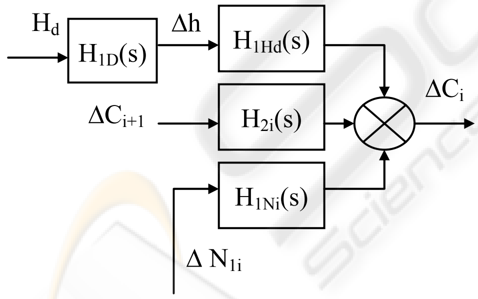

Figure 4: Block diagram of one basin.

1 to 6 can be linearized around the stationary values and simplified, resulting the schematic block diagram presented in figure 4.

The transfer functions are the following form:

$$H_{1Hd}(s) = \frac{b_{1i}s + b_{0i}}{a_{2i}s^2 + a_{1i}s + a_{0i}} \qquad (5)$$

$$H_{2i}(s) = \frac{b_{1i}s + b_{2i}}{a_{2i}s^2 + a_{1i}s + a_{0i}} \qquad (6)$$

$$H_{1Ni}(s) = \frac{b_{1i}s + b_{3i}}{a_{2i}s^2 + a_{1i}s + a_{0i}} \qquad (7)$$

The interconnection between basins 1 to 6 is done through the transfer flow between basins:

$$F_{ei} = \mu_i.A_i\sqrt{2g(H_i - H_{i-1})} + k_{pi}.F_{pi}, i = 1,2,...5$$

where: $\mu_i = 1/\sqrt{1{,}5 + \lambda_i L_i / D_i}$,

$\lambda_i = 0{,}86(1 + 2/(H_i + H_{i-1}))^{1/3}$,

$A_i = 0{,}5D_i(H_i + H_{i-1}), k_{pi} = (1..3), V_i = S_i.H_i$

and the return flow is: $F_{ri} = N_i * F_{pi}$

Combining all 5 active basins, we obtain the block diagram in figure 5.

3 AUTOMATIC CONTROL OF THE AERATION BASINS

In order to determine the optimal structure of the automatic control system for the oxygen concentration in the biological treatment basins, the mathematical model of the basins was developed, using the technological diagram (figure 1) and the available controls for the oxygen concentration. We tried to get a better approximation of the real process than the one used in (Vinatoru, 1979); therefore it considered the influences at the border between two basins.

Analysing the existing conditions in the aeration basins, we can divide the installation in two big sectors:

- in the first sector, containing basins 1,2 and 3, the oxygen concentration control is done through the number of running aerators N_{1i} and through the height of the dam H_d (figure 4);
- in the second sector, containing basins 4 and 5, the oxygen concentration control is done through the number of running aerators N_{2i}.

The high cost of oxygen sensors and especially the high maintenance cost call for reduction of the number of sensors used. From the analysis of the biological water treatment basins at DOLJCHIM SA Craiova, where the experiments were also made, we determined that a minimum of two sensors are necessary, one being mounted at the exit (measuring concentration C_1) and one in basin 4 (measuring concentration C_4). These measurements will be used as output variables for the controlled process. The right control strategy and structure to be used depends of the financial capability of the company. We studied three different control structures that can be used for similar basins.

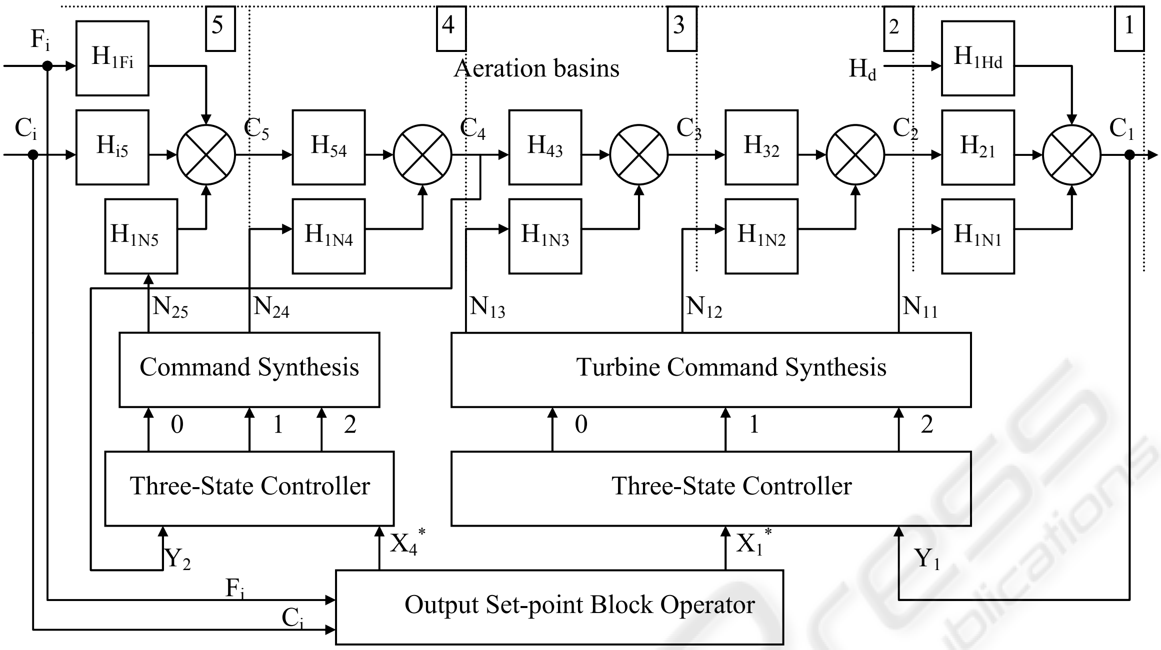

Figure 5: Conventional control diagram.

- Conventional control structure using tri-positional controllers, figure 5, which control the starting and stopping of the aeration turbines depending of the domain in which the oxygen concentrations in basins 1 and 4 are located, according with the algorithm presented in Table 1. This solution was implemented for the biological treatment basins. The control devices for the number of aerators and the actuator for the dam can be easily implemented and their control by the tri-positional controller is done based on the limits C_{min} and C_{max} according with table 1, imposed by the particular conditions inside the aeration basins.

Table 1: Control algorithm.

Control aerator basins 1,2 and 3			
Concentration C_1	0	C_{min}	C_{max}
Aerator running	All	1,3,5,7,9	3,5,7
Dam	Upper position	Upper position	Lower position
Control aerator basins 4 and 5			
Concentration C_4	0	C_{min}	C_{max}
Aerator running	All	11,13,15	11,15

From equations 1 to 6, considering the particular conditions for the aeration basins, it results that the entire process has a very slow dynamic regime, due to the high volume of wastewater compared with the transit time of the water in the basins. Therefore is not necessary a continuous control of the oxygen concentration. Moreover, the bacterial activity does not require an exact oxygen concentration but certain limits between which the activity is running normally.

- Fuzzy control structure, where the fuzzifier and the defuzzifier are following the control rules presented in table 1.

- Control structure using state estimators according with the diagram presented in figure 6. For this structure, the current state in each basin

X1 = C_1, $X_2 = C_2$, $X_3 = C_3$, $X_4 = C_4$, $X_5 = C_5$, is estimated based on the measured output values $Y_1 = C_1$, $Y_2 = C_4$.

Using the state variables and applying the command synthesis principles developed by the authors for the control of distributed parameter systems (Vinatoru 1979), the command for the aeration turbines will be generated by the Command Synthesis block in figure 6.

4 CASE STUDY

4.1 Control with Two Tri-positional Controllers

To show the performance and experimental results behaviour of the control structures some experiments have been carried out. The conventional control structure using tri-positional controllers has implemented to the DOLJ Chim SA Wastewater Treatment Plant Craiova.

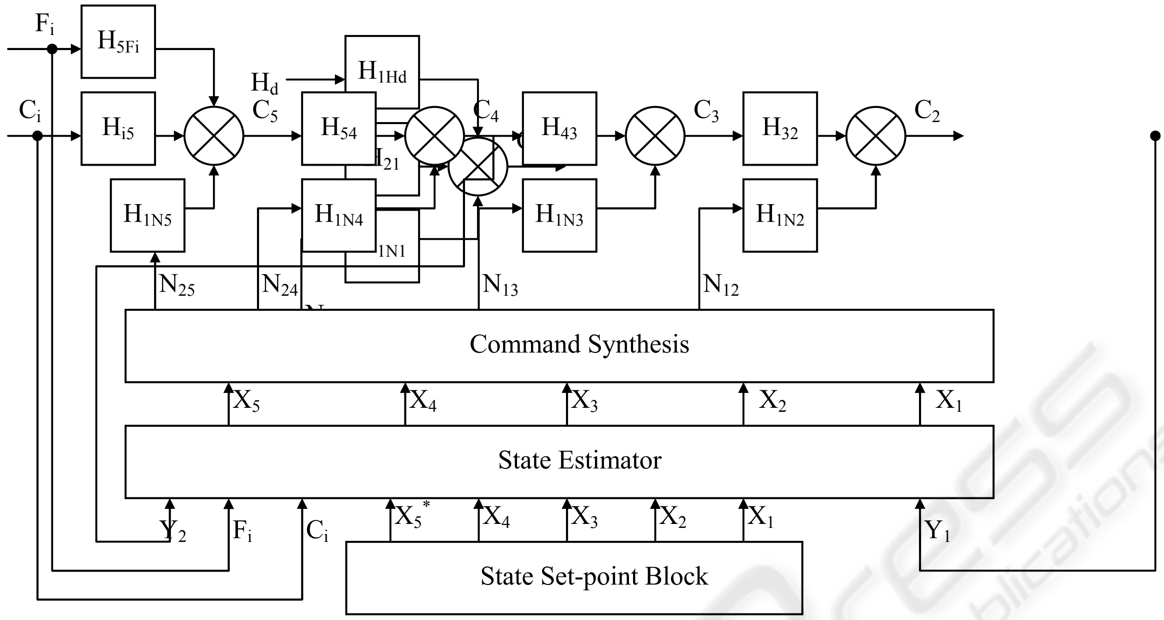

Figure 6: Advanced control diagram.

The experimental results in the various conditions of residual water flow are presented in figure 7. Aeration basins volume: 54.000 m^3 (9000 m^3/basin); Internal recycle flow rate 2700 m^3/hour; Dissolved Oxygen concentration (DO): 6 mg/l basin no. 1 and 4 mg/l in basin no. 4.

4.2 Control using a Sate Estimator

To sow the performance behaviour of advanced controller structure, the proposed control strategy has been implemented to the model of Wastewater purification Plant, presented in figure 6. The transfer functions from this structure are:

$$H_{21}(s) = \frac{0.66(80.4s+1)}{1397s^2+97.73s+1} = H_{32} = H_{43} = H_{54}$$

$$H_{1Ni}(s) = \frac{2.8(91.12s+1)}{1344s^2+96.72s+1}, i = 1...5$$

$$H_{i5}(s) = \frac{0.78(80.4s+1)}{1397s^2+97.73s+1}$$

According with the diagram presented in fig. 6 the state estimator has implemented in the form:

$$\frac{d\hat{x}(t)}{dt} = A_0(q)x(t) + C_0 w(t) \qquad (8)$$

where q is elements of the unknown vector considered the tuning parameters of the observer. The input w(t) is:

$$w(t) = c.u(t) + g^T Q(\hat{y}(t) - y_m(t)) \qquad (9)$$

where g^T is the weighting functions and $Q \in R^2$ is introduced for a better tuning of the observer parameter in function of the difference between the estimated output $\hat{y}(t)$ and the real output $y_m(t)$ ($y_{m1}=C_1$, $y_{m2}=C_2$). We have implemented the command synthesis in function of each estimated steady state variables $x_i=C_i$ *(I=1...5),* controlled by inputs N_{ij} (see diagram from fig. 6).

The results are presented in figure 7.

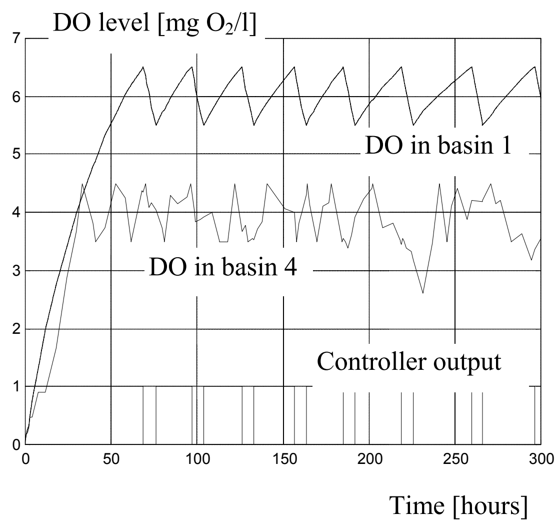

Figure 7: Experimental results I.

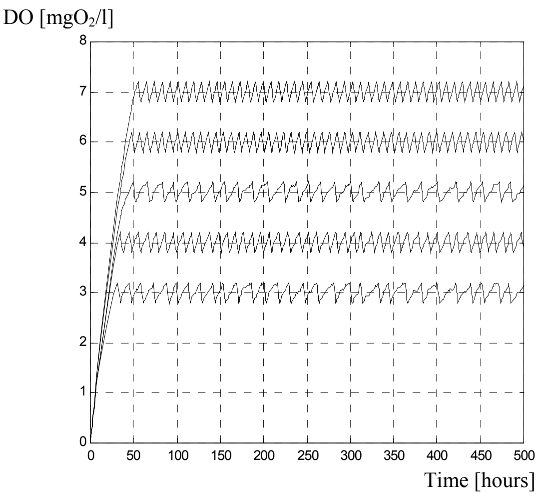

Figure 8: Experimental results II.

5 CONCLUSIONS

The results obtained using the proposed control structures to a Wastewater purification Plant are satisfactory. It causes a better performance of the plant because environmental law nearer to those requires the level of purification obtained. Also, the running costs have a notable reduction. The conventional tri-positional control structure is in implementation phase and we study the possibilities for advanced control structure. The results obtained till now establish the steps towards this objective.

REFERENCES

Chen W. C, Chang Ni-Bin, Shieh Wen K, Advanced hybrid fuzzy-neural controller for industrial wastewater treatment, Journal of environmental engineering , ISSN 0733-9372 CODEN JOEEDU , 2001, vol. 127, n°11, pp. 1048-1059

Chang Ni-Bin, Chen W. C, Shieh Wen K, Optimal control of wastewater treatment plants via integrated neural network and genetic algorithms, Civil engineering and environmental systems (Civ. eng. environ. syst.) ISSN 1028-6608, 2001, vol. 18, n°1, pp. 1-17

Demey D, Vanderhaegen V, Vanhooren H, Liessens J, Van Eyck L, Vanrolleghem P. A, Hopkins L., Validation and implementation of model based control strategies at an industrial wastewater treatment plant, Water science and technology (Water sci. technol.) ISSN 0273-1223, CODEN WSTED4 , 20011981, vol. 44, n° 2-3, pp. 145-153,

Henze M., Grady C.P.L., Gujer W., Marais G.V.R., (1987), *A general Model for Single-sludge Wastwater Treatment Systems,* Water Resourses, Vol. 20, pp. 505-515.

Ng Wun Jern, (2006), Industrial wastewater treatment, *National University of Singapore* , World Scientific Publishing, ISBN 978-1-86094-580-9

Peter A. Vanrolleghem, Models in Advanced Wastewater Treatment Plant Control (2003), Water Res. 2003 Jan;37(1):95-107, ELSEVIER

Urrutikoetxea A., Garcia de las Heras J.L., (1994), *Secondary Settling in Activated Sludge. Alab-scale Dynamic Model of Thickening,* Proceeding of the 8th Forum for Applied Biotechnology, Gent Coupure Links 653, B-9000, Gent Belgium.

Vinatoru M. , Niculescu E. ,Mihaiu M., (1979), The automatic compensation with the temperature of the oxyfen sensore –„3rd International Symposium on Control System and Computer Sciens – Bucureşti , , vol.III.p.654-660

Yusof R., Omatu S., (1993), *A multivariable self-tuning PID Controller,* Int. J. Control, Vol.57, No. 6, pp. 1387-1403.

APPENDIX

Notations and Symbols

V_i – volume of basin i (i=1-5) [m^3], F_{ei} - output flow from basin i (F_6=0) [m^3/h], F_{ia} – input wastewater flow in basin i [m^3/h] (F_{la}=0), F_{in} – input flow of activated sludge in basin i [m^3/h] ($F_{ln}=F_{2n}=F_{3n}=F_{nn}=0$), C_i – oxygen concentration in basin i [mgO_2/l], C_{in} - oxygen concentration in flow F_{in}, C_{ia} – oxygen concentration in flow F_{ia}, C_a– oxygen concentration at working temperature, K_{Au} – transfer coefficient in wastewater
F_{ri} – recirculation flow of aeration pumps [m^3/h]
C_{ri} – oxygen concentration in flow F_{ri}
γ -specific gravity of the medium inside the basin [N/m^3]
n - nominal rotational speed of the pumps, n_a – specific rotational speed of the pumps, h_i – immersion depth of the aerator [m], F_{pi} – pump flow [m^3/s], H_i –water level in the basin i [m], L_i –width of the separation wall [m], D_i – width of the transfer section between two basins, K_{pi} – ratio coefficient between pump flow F_{pi} and exit flow
S_i –area of horizontal section through the basin [m^2], N_i – umber of running pumps in basin i, m_c –shape coefficient, depending of the geometric shape of the dam, b –dam width, H –the liquid level above the dam, M_l –coefficient of velocity, depending of the access speed upstream of the dam, l_d –dam height [m].