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Dedicated to Professor Ion Grosu
on the occasion of his 65th anniversary

OPTIMIZATION AND CONTROL OF AERATION DISTRIBUTION IN THE WWTP NITRIFICATION REACTOR

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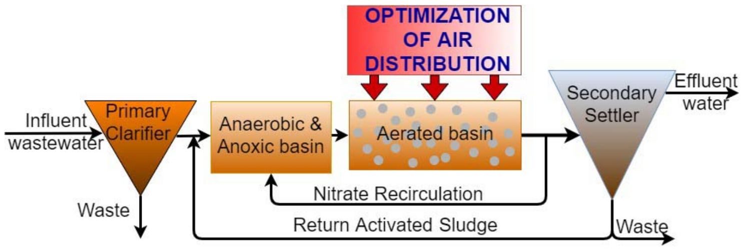
The aerated biological reactor of the Waste Water Treatment Plant (WWTP), operating on the basis of the active sludge technology, is recognized as the major energy consumer of the WWTP. Automatic control of the nitrification treatment step plays a major role both for satisfying the required quality of the effluent water and for whole plant energy efficiency. The paper presents a solution for finding the optimal distribution of aeration along the nitrification reactor, in association to ammonia automatic control. The incentives of the proposed nitrification control approach are investigated by two control system structures. They have the ammonia master controller acting either on the setpoints of the Dissolved Oxygen controllers, in a supervisory control design, or manipulating the air flow rate along the reactor by the Dissolved Oxygen slave controllers, in a cascade setup. Investigations were performed for an Anaerobic-Anoxic-Oxic municipal WWTP case study. The benefits of the proposed control structures are revealed by assessing the Pumping Energy, Aeration Energy and Effluent Quality performance indices.



INTRODUCTION

Waste Water Treatment Plant (WWTP) operation control is an essential issue as a result of the large influent wastewater concentration and flow rate disturbances, the high operation costs due to the increased aeration and pumping energies consumed and the strict legal restrictions for the effluent pollutant concentration.[1–9] The activated sludge technology is the most well-known and widespread applied technology at the municipal WWTPs.[10] This technology requires two main biochemical steps: nitrification and denitrification.[11] In the nitrification step the saline and free ammonia from the influent wastewater is oxidized to nitrite and nitrate. This process requires a significant amount of air for the transfer of oxygen from the gaseous phase to liquid phase (Dissolved Oxygen, DO). The preparation of the air by the air blowers is one of the most energy intensive processes.[12] It was reported that the aeration energy is more than 50% of the total energy consumed at the municipal WWTPs.[13] In the denitrification step the nitrates and nitrites are transformed to nitrogen gas which is eliminated in the ambient.

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Ammonia is one of the main pollutants to be removed from the sewage. Ammonia based aeration control may be performed by a cascade automatic control strategy. The cascade control design consists in a master ammonia controller and one or more slave Dissolved Oxygen controllers.[14–16] The ammonia concentration in the outlet of the aerated zone of the biodegradation basins is the controlled variable. The setpoint of the ammonia master controller is chosen by the overall control strategy considerations, while the ammonia controller generates and provides the setpoint value for the Dissolved Oxygen concentration controller. The manipulated variable of the Dissolved Oxygen controller sets the air flow rate required in the aerobic zone, the flow rate of the air being the manipulated variable.[17]

The understanding of the activated sludge process behavior and the subsequent investigation of different automatic control designs are assisted by mathematical modelling and simulations.[18–24] Activated Sludge Model (ASM) No. 1, 2, 2d and 3 are reported as the most commonly used activated sludge models in the field of municipal wastewater treatment.[25] ASMs describe the removal of organic pollutants, nitrogen components and phosphorus pollutants from sewage. The Benchmark Simulation Models (BSMs) represent valuable and very efficient instruments for investigating new design and control solutions for the WWTPs operation. BSMs introduce, besides the biochemical processes described by the ASMs, the models for the physical separation of the suspended solids in the secondary settler and complement them with two automatic control loops. The first one is the Dissolved Oxygen control loop, controlling the dissolved oxygen concentration in the outlet of the aerobic zone by manipulating the air flowrate (oxygen transfer coefficient value), and the second one consists in the nitrates and nitrites control loop, controlling the nitrates and nitrites concentration in the outlet of the anoxic zone by acting on the nitrate recirculation flow rate.[26–28]

This research presents the investigation of aeration control and its associated aeration energy savings at a Romanian municipal WWTP by finding the optimal air distribution in the aerobic biodegradation basins. Two automatic control strategies, a supervisory and a cascade control design, were studied by mathematical modelling and simulation, using a previously calibrated dynamic WWTP model based on the Activated Sludge Model No. 1 (ASM1) and Benchmark Simulation Model No. 1 (BSM1). The novelty of the present work consists in the proposed control system designs applied for the ammonia-based aeration control, in association with the use of the optimization approaches for finding the optimal air distribution and its control along the aerobic zone of the biodegradation basins. Investigations were carried out on the case study of a municipal waste water treatment plant.

RESULTS AND DISCUSSION

1. Roumanian municipal WWTP

The Roumanian municipal WWTP under study has an Anaerobic-Anoxic-Oxic (A^2O) configuration, as presented in Fig. 1. The nitrate recirculation is the particular characteristic of this layout. In order to perform the denitrification step this internal recycle is returning the water flow with rich nitrates and nitrites components from the outlet of the aerobic zone and introduces it before the anoxic zone of the denitrification reactor.[29]

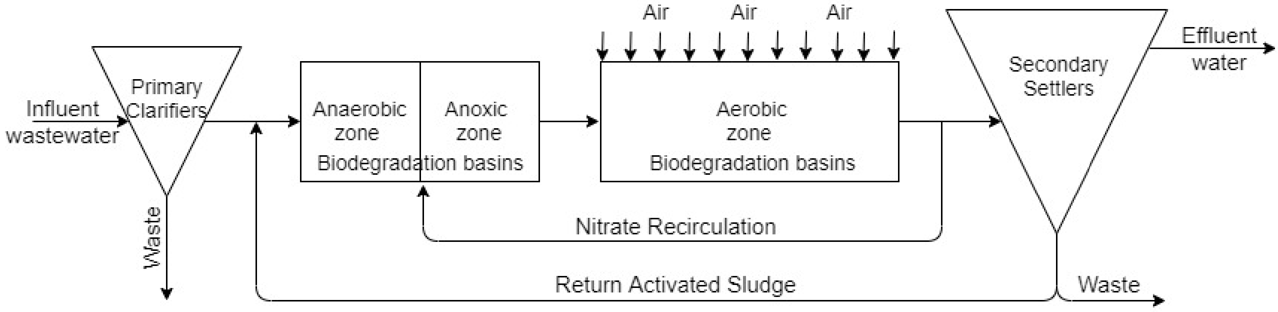

Fig. 1 – The Roumanian municipal WWTP configuration.

The wastewater from the city sewage network is entering the WWTP having the maximum capacity of the 13000 m^3/h. The first step of the sewage treatment consists of the primary physical processes: gross and fine filtration, sand and fats separation and primary sedimentation. Following these steps, the emerged wastewater is fed to the anaerobic zone, followed by the anoxic zone of the biodegradation basin. The task of the anaerobic biodegradation basin is the growth of the phosphorus accumulating microorganisms, while the role of the anoxic biodegradation tank is the elimination of nitrates and nitrites formed in the nitrification reactors. The anaerobic and anoxic tanks are followed by the aerobic biodegradation tanks, in which the organic matter is transformed by assimilation into microorganisms, the phosphorous is accumulated by phosphorus accumulating microorganisms and the ammonia is oxidized to nitrates and nitrites. The last step of the activated sludge technology is the sludge separation from the liquid-solid mixture. This is achieved in the secondary settler and, subsequently, the cleared water is sent to the emissary river. This WWTP configuration includes two recycle streams. The first one is the nitrate recirculation (internal recycle stream). It recycles the mixed liquor from the outlet of the aerobic biodegradation basins to the inlet of the anoxic zone. The second one, *i.e.* the return activated sludge (external recycle stream), is recirculating the largest part of the activated sludge obtained at the bottom of the secondary settler to the inlet of the anaerobic zone of the denitrification tanks.

2. Dynamic WWTP model

The dynamic WWTP model was developed according to the configuration of Benchmark Simulation Model No. 1 (BSM1) and it consists of a primary clarifier model, 5 models of the bioreactors connected in series and a secondary settler model.[30] The primary settler model was developed based on the Otterpohl and Freund clarifier model.[31] The models of the bioreactors are based on the modified Activated Sludge Model No. 1 and consist in an anaerobic bioreactor, an anoxic bioreactor and three aerobic bioreactors.[32] According to ASM1, each of the anaerobic, anoxic and the three nitrification bioreactors are modeled as continuous stirred tank reactors. The secondary settler model includes the model equations and the double exponential velocity function defined by Takács *et al*.[33]

The developed model was calibrated with construction data provided by the municipal WWTP and with operation data collected during May 2016. Concentration of the Chemical Oxygen Demand, Ammonia, Nitrates and nitrites, Total Nitrogen, Total Suspended Solids, both in the influent wastewater and in the effluent cleared water, have been obtained from the on-site measurements or as results of the calibration step. They were associated to the measured flow rates for the influent, effluents, nitrate recirculation and return activated sludge recirculation flows. This WWTP model, previously calibrated by different optimization approaches,[34] was used in this research.

3. Air distribution control strategies

In this research two automatic control structures were proposed for the ammonia based aeration control.

The first control strategy, scenario A, is a cascade control design presented in Fig. 2. In this scenario, the previously calibrated model was augmented with a control system consisting of 3 feedback Dissolved Oxygen controllers in a cascade setup. All of the three DO slave controllers are Proportional-Integral (PI) and for the ammonia (NH) master controller a PI control law was also considered. The ammonia concentration in the outlet of the aerobic biodegradation basin is measured and compared with the predefined ammonia setpoint value for generating the error. Based on the control error value, the NH controller computes the setpoint value for the third DO controller which is compared with the dissolved oxygen measured concentration in the last bioreactor. The third DO controller computes the dissolved oxygen setpoint value for the second DO controller, which is compared with the dissolved oxygen concentration measured in the fourth bioreactor. Based on the same approach, the second DO controller computes the setpoint value for the first DO controller, which compares the control signal with the concentration of dissolved oxygen measured in the third bioreactor (i.e. the first aerated bioreactor). Finally, the first DO controller computes the necessary air flow rate to be fed in the aeration bioreactors. At the analyzed plant the air flowrate is equally introduced along the aerobic biodegradation basin. As the objective of the present study is to find the optimal air distribution along the nitrification tanks (i.e. the best distribution of air among the three aerated bioreactors), the manipulated variable value of the first DO controller was multiplied by the different factors: a, b and c. According to the values of these factors the air distribution in the aerobic bioreactors may be distributed unequally and optimal.

The second control design, scenario B, has a supervisory control setup as it is presented in Fig. 3. The calibrated WWTP model was supplemented with three feedback PI Dissolved Oxygen controllers. The first DO controller regulates the dissolved oxygen concentration in the third bioreactor (first aerobic bioreactor) by manipulating its inlet air flow rate. The second and third DO controllers control the dissolved oxygen concentration in the fourth and fifth bioreactors (second/third aerobic bioreactors). The setpoint value for the all three DO controllers is computed by a supervisory ammonia controller. The value of the NH controller manipulated variable is multiplied by three different but optimized weighting factors, generating the setpoints for each of the three DO controllers. The target of the NH controller is to keep the ammonia concentration in the last aerobic bioreactor at its desired setpoint value, while optimally distributing the air flowrate among the three aerobic bioreactors.

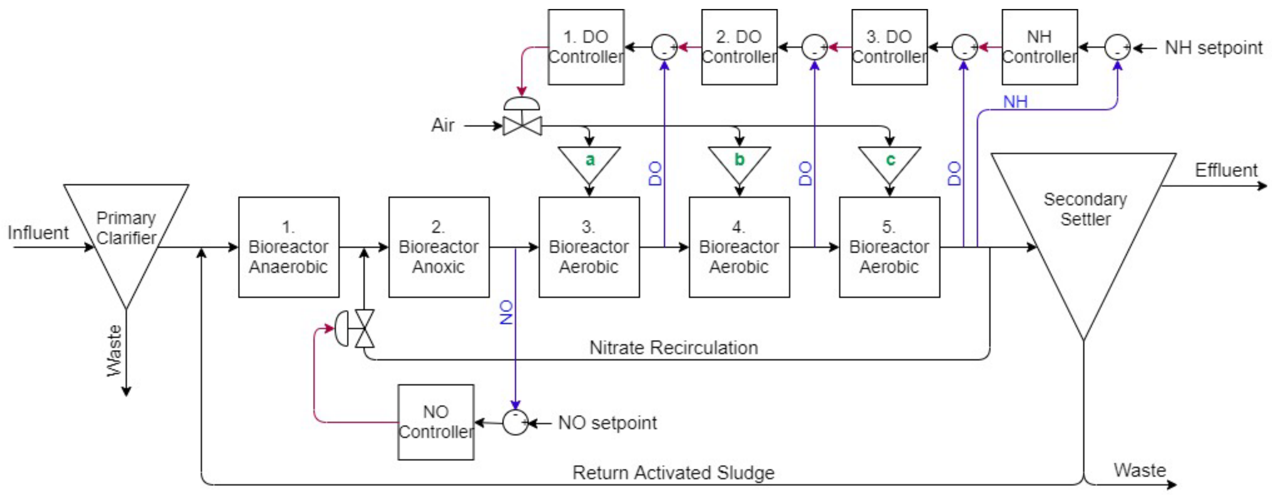

Fig. 2 – Scenario A: Aeration control in cascade configuration.

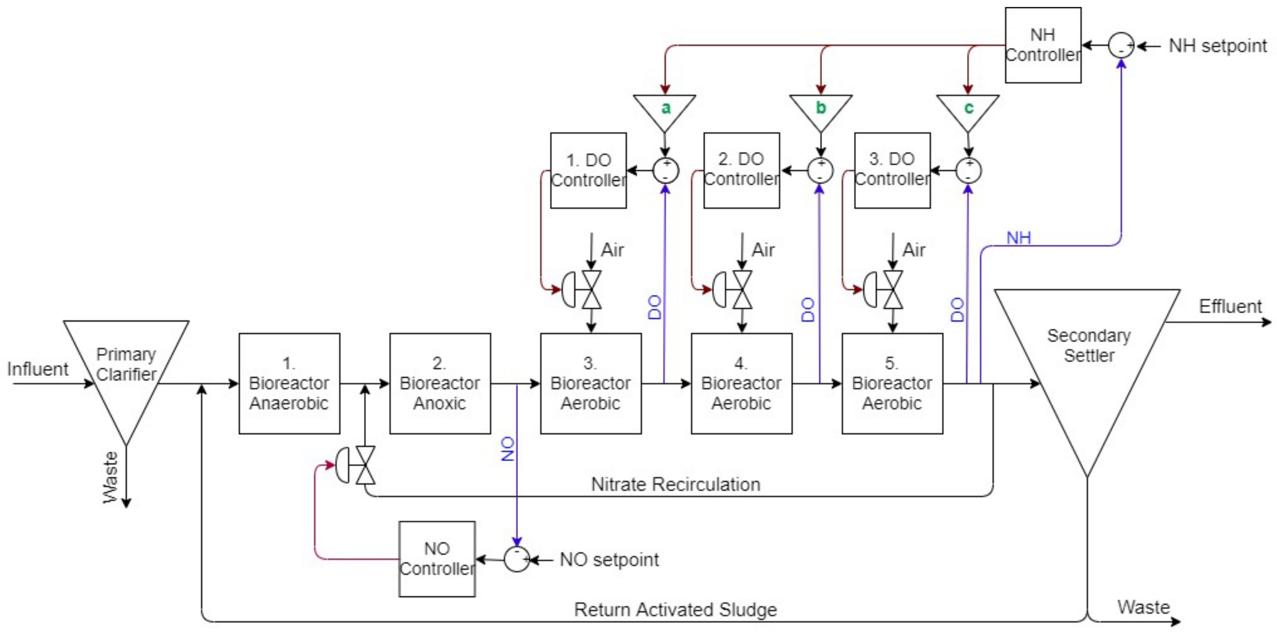

Fig. 3 – Scenario B: Aeration control in the supervisory configuration.

For both control design scenarios, the concentration of the nitrate at the outlet of the anoxic zone was also considered to ensure appropriate nitrification. The nitrate (NO) controller was added to the control configurations for keeping the nitrate and nitrites concentration in the anoxic zone at the desired setpoint value by manipulating the nitrate recirculation flow rate. The NO controller is also operating on the basis of a PI control law.

4. Optimization of air distribution

The aeration being an energy intensive process, it is necessary to find the optimal air distribution along the aerated biodegradation basins for satisfying the expected WWTP performance. An optimal air distribution may reduce the operation costs by sparing the aeration and pumping energy but may also improve the effluent quality.

Two optimization approaches were taken into consideration for the designed aeration control strategies (control scenarios A and B). For all cases, the goal was to find the optimal value of the WWTP performance index, evaluated by a cumulative performance function composed of aeration energy, pumping energy and effluent quality.[24] The aeration energy is formulated based on the oxygen mass transfer coefficient of the aerobic bioreactors (K_La), which is directly depending on the air flow rate, as showed in Eq. (1).[26, 28] The pumping energy takes into account the flow rates of nitrate recirculation, return activated sludge recycle and waste, as described by Eq. (2).[26, 28] Correction factors were used for the aeration and pumping energy (C_{AE} and C_{PE}). They were set based on the measured data collected from the municipal WWTP. The aeration and pumping energy are expressed in kWh/day units. The effluent quality considers the Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Kjeldahl Nitrogen (TKN) and Nitrates and nitrites (NO) concentrations in the effluent flow stream, as described by Eq. (3).[27, 28] The effluent quality is expressed in kg pollutant units/day.

$$AE = C_{AE} \cdot \frac{SO\_sat}{T \cdot 1.8 \cdot 1000} \int_0^T \sum_{\text{aerated units}} V \cdot K_L a_i(t)\, dt \tag{1}$$

$$PE = C_{PE} \cdot \frac{1}{T} \int_0^T \left[0.004 \cdot Q_{NR}(t) + 0.08 \cdot Q_{RAS}(t) + 0.05 \cdot Q_{waste}(t) \right] dt \tag{2}$$

$$EQ = \frac{1}{T \cdot 1000} \int_0^T \left[PU_{TSS}(t) + PU_{COD}(t) + PU_{BOD}(t) + PU_{TKN}(t) + PU_{NO}(t) \right] \cdot Q_{effluent}(t) dt \tag{3}$$

In Eqs. (1-3) V is the volume of each of the three aerated bioreactors, T is the investigated period of 22 days and the other factors or constants were taken from literature.[26-28]

In order to evaluate the overall WWTP performance, the objective function of the optimization problem is the sum of the aeration energy, pumping energy and effluent quality for both investigated scenarios. Importance given to the terms in the objective function is based on the observation that the sum of the aeration and pumping energy value is approximately equal to the effluent quality value. The decision variables differ. For scenario A, the air distribution is optimized based on the manipulated variable of the first DO controller, which defines the necessary raw air flow rate entering the 3 bioreactors. The control signal value is multiplied by the different constant factors a, b and c, associated to the three aerated bioreactors. They are denoted with x_1, x_2, x_3 in the optimization problem. Based on their values it may be directly computed the air flow rate for each of the aerated bioreactors. For scenario B, the decision variables are the setpoint values of the three DO controllers. In this case the control signal of the NH controller is multiplied by the different constant factors a, b and c (denoted again by x_1, x_2, x_3, in the optimization problem). They provide the dissolved oxygen setpoint values in the three aerobic bioreactors. Lower and upper bounds (LB and UB) were defined for the decision variables.

Eqs. (4-7) summarize the formulation of the optimization problem.

$$\min_X \left[objfunc\left(x_1, x_2, x_3\right) \right] \tag{4}$$

$$X = \left[x_1, x_2, x_3 \right] \tag{5}$$

$$objfunc = AE + PE + EQ \tag{6}$$

$$LB \le X \le UB \quad (7)$$

In all investigated scenarios, the influent and measured data of the first 22 days of the month May 2016 were considered and performance index was evaluated.

5. Performance evaluation

In order to have a reference for comparison, the performance of the municipal WWTP under study was first determined without the proposed control scenarios. The aeration energy, pumping energy and effluent quality were computed using only measured data collected during ordinary operation of the plant. The values of the performance sub-indices, obtained for the 22 days of May 2016, are presented in Table 1.

Optimization was carried out using two optimization methods. The first one is the classical optimization method and relies on the classical interior point algorithm which combines a direct Newton step with a conjugate gradient step. The second one is the genetic algorithm which starts with a population of points (initial generation) that are improved at next generations of the population by mutation and crossover, until the best individual in the population is discovered. In the all optimization scenarios the setpoint value of ammonia NH controller was set to the value of 0.5 g N/m^3. For scenario A of the cascade control system design, the optimization results are shown is Table 2.

Table 1

The performance sub-indices of the municipal WWTP

Performance index	Value	Unit
Aeration energy (AE)	13720.1	kWh/day
Pumping energy (PE)	7583.7	kWh/day
Effluent Quality (EQ)	19436	kg P.U./day
AE + PE + EQ	40739.8	-

Table 2

The values of the decision variables obtained for the cascade control system design (scenario A)

Decision variables	Optimization by classical algorithm	Optimization by genetic algorithm
a : b : c ($x_1 : x_2 : x_3$) [Q_{air} (R3) : Q_{air}(R4) : Q_{air}(R5)]	10.3 : 1 : 1	20.3 : 21.3 : 1

Table 3

The performance sub-indices and the effluent pollutant concentrations obtained for the cascade control system design (scenario A)

Performance index / Effluent concentration	Optimization by classical algorithm	Optimization by genetic algorithm	Unit
Aeration energy (AE)	11272.7	11164.5	kWh/day
Pumping energy (PE)	7550.0	7458.0	kWh/day
Total energy	18827.7	18622.5	kWh/day
Effluent quality (EQ)	14166.4	15241.9	kg P.U./day
AE + PE + EQ	32994.1	33864.4	-
Q_{air} (R3)	288614	154124	m^3/day
Q_{air} (R4)	27946	161433	m^3/day
Q_{air} (R5)	26954	7646	m^3/day
COD Effluent	21.4339	21.3204	g COD/m^3
Ntotal Effluent	3.5158	3.9770	g N/m^3
NO Effluent	1.2522	1.7182	g N/m^3
NH Effluent	0.4956	0.4924	g N/m^3
TSS Effluent	12.0990	12.0965	g SS/m^3

From the results presented in Table 2 it may be observed that in the first part of the nitrification basin the flow rate of the air entering the bioreactor is higher than at the end of the biodegradation tank. This is true for both cases of the different optimization methods. Optimization by classical algorithm shows that the air flowrate entering the fourth and fifth bioreactors is equal and only in the third bioreactor (i.e. the first of the aerated bioreactors) is required a high air flow rate. Optimization by genetic algorithm reveals that in the first two aerated bioreactors higher air flow rates are necessary, compared to the last one.

Table 4

The values of the decision variables obtained for the supervisory control system design (scenario B)

Decision variables	**Optimization by classical algorithm**	**Optimization by genetic algorithm**
a : b : c ($x_1 : x_2 : x_3$) [SP (DO_R3) : SP(DO_R4) : SP(DO_R5)]	1.2 : 1 : 1.7	1.8 : 1.4 : 1

Table 5

The performance sub-indices and the effluent pollutant concentrations obtained for the supervisory control system design (scenario B)

Performance index / Effluent concentration	**Optimization by classical algorithm**	**Optimization by genetic algorithm**	**Unit**
Aeration energy (AE)	8871.9	9209.8	kWh/day
Pumping energy (PE)	7651.8	7749.2	kWh/day
Total energy	16523.7	16959	kWh/day
Effluent quality (EQ)	13605.1	13432.8	kg P.U./day
AE + PE + EQ	30128.8	30391.8	-
Q_{air} (R3)	112109	144412	m^3/day
Q_{air} (R4)	59844	66739	m^3/day
Q_{air} (R5)	55727	30413	m^3/day
COD Effluent	22.0034	21.8525	g COD/m^3
Ntotal Effluent	3.2298	3.1691	g N/m^3
NO Effluent	0.8262	0.8581	g N/m^3
NH Effluent	0.4944	0.4922	g N/m^3
TSS Effluent	12.1141	12.1102	g SS/m^3

Table 3 shows the performance sub-indices and the effluent pollutant concentrations for scenario A of the cascade control system design.

Results presented in Table 3 show that the overall performance of the WWTP is better when high air flow rate value is introduced only in the first aerated bioreactor (as revealed by the results of the optimization using classical algorithm). The effluent quality was improved when values of the decision variables obtained by classical algorithm optimization were applied for simulation, while the decision variables values of the genetic algorithm optimization resulted in small benefits for the total energy consumption. Compared to the reference case of the non-optimized aeration distribution, the aeration energy can be reduced by 17.8-18.6% when the proposed aeration cascade control system design and the values of the decision variables obtained by optimization are used. The effluent quality can be also improved, up to 27.1%, by implementing the proposed aeration cascade control design of scenario A.

For scenario B of the supervisory control system design, the optimization results are presented in Table 4.

Table 4 shows that the DO obtained according to the optimization using the classical algorithm for the setpoint value of the second aerated reactor should to be the lowest, while the DO setpoint values must decrease along the nitrification reactor according to the optimization using the genetic algorithm.

Table 5 presents the performance sub-indices and the effluent pollutant concentrations for scenario B of the supervisory control system design.

Results presented in Tables 4 and 5 drive to conclusion that aeration supervisory control design is the most favorable of the investigated control designs. The values of the performance sub-indices show the best WWTP results when applying this control scenario. The overall performance of scenario B presents the most favorable results when the decision variables values are obtained from the optimization based on classical algorithm. The total energy consumed is the lowest and the aeration energy can be reduced by 35.3%. The effluent quality can be improved up to 30.9% considering the results obtained from the optimization using the genetic algorithm. It may be also mentioned that the air flow rate is the highest in the first aerobic bioreactor, for both applied optimization algorithms.

EXPERIMENTAL

Online and off-line laboratory influent and recirculation flow rates or pollutant concentration measurements were performed at the investigated Romanian municipal WWTP in order to monitor the dynamic operation of the plant. The plant is equipped with an online Supervisory Control and Data

Acquisition system. The sampling time of the influent and effluent concentrations, influent and effluent flow rates, recycle streams and air flow rates was of 10 seconds. Daily or weekly sampled data were also obtained from the off-line laboratory measurements.

Matlab and Simulink graphical extension were used for the dynamic simulations of the WWTP model. Based on the calibrated model the changes of the pollutant concentrations and flow rates were computed by solving the associated system of differential equations. These equations were implemented in C programming language as S-function blocks and solved in the Simulink graphical environment associated to Matlab software.

Optimization was also performed using Matlab and Simulink software environment. The classical optimization algorithm was implemented by the *fmincon* Matlab function and for the genetic algorithm optimization the *ga* Matlab function was used.

CONCLUSIONS

This research proposes and presents results for computing the optimal air distribution in the aerobic bioreactors of a municipal WWTP, aimed to reduce the energy costs and to improve the effluent water quality. Two aeration control system designs were investigated, both of them based on the ammonia concentration control at the outlet of the last aerated bioreactor. The first one is a cascade control system design where the air flow along the aerobic zone is determined based on the control signal of the innermost dissolved oxygen controller manipulated variable multiplied by the optimal determined factors. The second one is a supervisory control system design where the setpoints of the dissolved oxygen controllers are computed based on the control signal of the ammonia controller multiplied by the optimal computed factors. For both proposed control designs the optimal air distribution was determined by optimizing the implied multiplying factors. Classical and genetic optimization algorithms were tested for finding the most efficient optimization method. The most favorable results were obtained by the optimized air distribution for the ammonia based aeration control in the supervisory configuration and using the classical optimization algorithm. For this control system structure, the overall performance of the municipal WWTP can be improved up to 26% due to the aeration energy reduction and effluent quality improvement. Although both investigated control configuration show incentives when compared to the non-optimal operation, the aeration in the supervisory control performs better than cascade control. Concluding, the optimal air distribution along the nitrification bioreactors may bring important benefits and can be implemented in the municipal WWTP for reducing energy consumption and plant performance improvement.

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NOMENCLATURE

A^2O	Anaerobic-Anoxic-Oxic
AE	Aeration Energy
ASM	Activated Sludge Model
BOD	Biochemical Oxygen Demand
BSM	Benchmark Simulation Model
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EQ	Effluent Quality
LB	Lower Bounds
NH	Free and saline ammonia
NO	Nitrates and nitrites
N_{total}	Total nitrogen
objfunc	Objective function
PE	Pumping Energy
PI	Proportional-Integral
Q_{air}	Air flow rate entering the bioreactor
SP	Setpoint
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
UB	Upper Bounds
V	Volume of each of the aerated reactors
WWTP	Waste Water Treatment Plant
X	Decision variables

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