Nonlinear Fuzzy Control System for Dissolved Oxygen with Aeration System in Sequencing Batch Reactor

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Abstract. Biological processes at a wastewater treatment plant are complex, multivariable, time varying and nonlinear. Moreover, interactions between the components are very strong. Control of dissolved oxygen is one of most important task at the plant. The level of dissolved oxygen in aerobic tanks has significant influence on behaviour and activity of microorganisms at the plant. Air for aerated tanks is supplied by the aeration system (blowers, pipes, diffusers), which is a complicated nonlinear dynamical system. A fuzzy control system for tracking the dissolved oxygen reference trajectory in activated sludge processes was proposed and investigated. The sequencing batch reactor was considered. The nonlinear aeration system dynamic was included. Two systems (sequencing batch reactor, aeration system) were modelled and validated. Inverse model of an aeration system was used to control system design. Dissolved oxygen is the control input, while the rotational speed and blowers on/off are control outputs. The nonlinear fuzzy control system was tested by simulation based on real data records sourced from a case study plant located in Swarzewo, Northern Poland.

Keywords: aeration; dissolved oxygen; wastewater treatment; Sequencing Batch Reactor; nonlinear system; control system.

1. Introduction

Biological processes at a wastewater treatment plant (WWTP) are complex, multivariable, time varying and nonlinear. Moreover, interactions between the components are very strong. Two different types of WWTPs are used in industrial practice: sequencing batch reactor (SBR) and WWTP with a continuous flow throughout the plant. The processes taking place during SBR operation, are carried out sequentially in a single tank. The other plant type uses separate tanks with recirculations (internal and external). The former type of a WWTP was considered in this paper.

A SBR system is very effective for nitrogen and/or phosphorus removal. Compared to continuous processes, a SBR is more stable, but requires tighter process control. This system is widely used for small wastewater inflows and may be designed using a single or multiple tanks in parallel configuration. This technology uses a sequence of fill and draw cycles. A classical cycle involves five operational phases: filling, reactions (nitrification and denitrification), sedimentation, decantation and idle state. This method offers great operational flexibility through the sequence of phases that may be adjusted to sustain any desired combination of growth conditions for biological reactions [1]. A detailed description of those processes

may be found in [2-3]. Mace and Mata-Alvarez [4] presented a complete review of experiences using SBR. Steinmetz and Wiese [5] described instrumentation, control techniques and control hardware used in different SBR plants.

Dissolved oxygen (DO) is one of the most important parameters to control. It is crucial for biological processes at WWTP and for energy saving related to aeration [6]. The DO tracking problem is one of the most complex and fundamental issues of biological processes at WWTP. On line sensors for DO measurements are cheap and generally available at WWTPs. Different control strategies for DO control in SBR have been intensively investigated over the past few years. The Mamdami type of fuzzy logic controller was presented in [7] and it has been applied in a pilot batch reactor. In [8], the neural control system was designed and tested. Kim et al. [9] described the results of simulation using iterative dynamic programming-based optimisation for four different influent loadings. In [10], fuzzy controller with Smith predictor for DO control was applied.

The main objective of the aeration process control at WWTP is to provide the necessary oxygen supply for different biological reactions. These processes (denitrification, nitrification, phosphorus removal) are strongly

dependent on concentration of DO. Moreover, aeration is very expensive to carry out. The total of energy consumed by aeration processes is the factor deciding about total energy consumption of a WWTP.

Advanced control methods (e.g. predictive control) often require substantial modifications and updates to the hardware-software structure at WWTP and extensive staff trainings. Fuzzy control systems are simple to implement in an existing structure. Moreover, knowledge of WWTP staff helps to design fuzzy rules for control strategy. Thus, it is a very important tool for designing novel control systems for a WWTP.

Fuzzy logic may be applied in several ways to control DO concentration at a WWTP [7, 11-13]. In all cases, the nonlinear dynamic of aeration system is omitted. A large advantage of this paper, as opposite of previous research works, is designed model of an aeration system and it's coupled with a model of biological processes. The model of an aeration system was included for control system purposes. The

nonlinear fuzzy PI controller for DO tracking and aeration system control was designed at and used in the Swarzewo WWTP case study. Simulation results based on real data records were presented and analyzed.

2. WWTP description and modelling

2.1. Description of the case study WWTP

WWTP at Swarzewo (Northern Poland) is a typical SBR plant. The average WWTP influent is about 6000 m^3/day of waste. Wastewater treatment involves mechanical, biological and chemical processes. Fig. 1 shows the SBR pilot plan diagram. Purification of sewage solids takes place in the mechanical part (grid, screen, grit chamber, sand separator). The chemical part is used to remove phosphorus from wastewater using coagulants. In this paper, the biological part of a WWTP is considered.
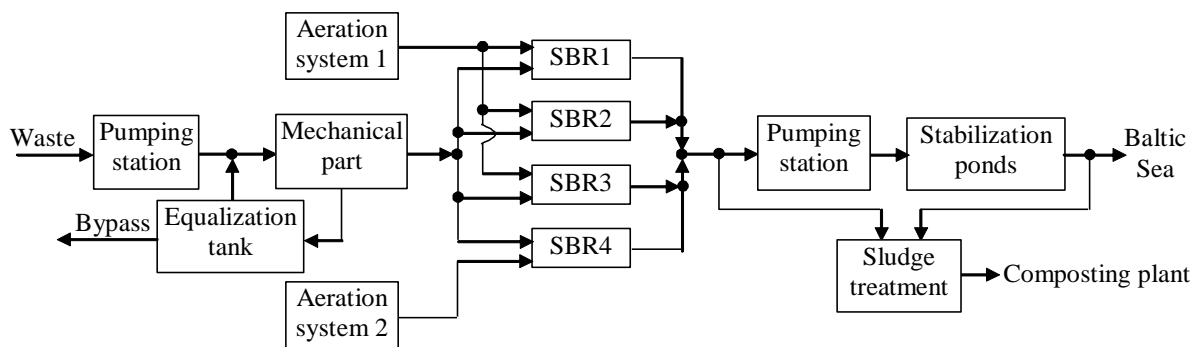

Figure 1. Technological diagram of the case study WWTP

Removal of biological pollutant is performed by four SBRs. SBR capacities are as follows: SBR 1, 2, 3 are of 5100 m^3, SBR 4 is of 6400 m^3. They operate in parallel and independently. A single SBR cycle involves the following phases: filling, reactions (nitrification and denitrification), sedimentation, decantation and idle state. During the reactions phase, alternating aerobic, anoxic and anaerobic conditions are necessary to successfully remove nitrogen and phosphorus. A predefined 8h step-feed cycle is used.

Air supply for the reactors is fed by two identical, independent aeration systems (see Fig. 1). The first of these aerates three SBRs (1, 2 and 3). The second installation supports SBR 4. It was applied in this paper. The only variable measured at SBR 4 is DO.

The excess waste sludge is removed, chemically stabilized and stored. The Baltic Sea is the effluent receiver.

2.2. Activated sludge model

Activated sludge models (ASMs) proposed by International Water Association task group are the most popular mathematical description of the biological processes taking place at a WWTP. Models (ASM1, ASM2, ASM2d, ASM3) were presented and summarized in [14]. ASM3 Bio P [15] was a result of

further research efforts. In this paper, biological processes were modelled using the ASM2d model [16]. It consists of 21 state variables and 20 kinetic and stoichiometric parameters. These parameters were equal to their default values at 20°C [16]. ASM2d model was calibrated based on real data sets from WWTP at Swarzewo. Additionally, the input values of: chemical oxygen demand (COD), total nitrogen concentration (N_{tot}) and total phosphorous concentration (P_{tot}), were determined. Modelling results were verified to be satisfactory and next they were used for control purposes.

3. Aeration system

3.1. Structure of the aeration system

The aeration system is a complicated nonlinear dynamical system with fast dynamics. Different ways of aerations are used: high purity oxygen aeration, mechanical aeration and diffused aeration [17]. In this paper, the last method was used. Air is supplied to the SBR 4 by the aeration system 2 (see Fig. 1). That system is composed of a blower station, collecting pipe, two diffuser systems and collector-diffuser pipes (Fig. 2).
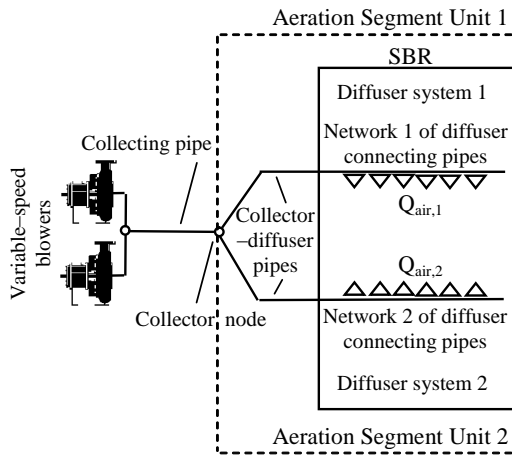
Figure 2. Structure of the case study aeration system

Two identical blowers operating at variable speed with inverters were used. The blowers are in parallel configuration. The relationship between airflow through the blower and the pressure drop across the blower is nonlinear. Blowers' operating pressure range is 30-85 kPa and airflows range is between 700-3700 m^3/h (Fig. 3). In practice, the aeration system operates under pressure of about 70 kPa with airflows ranging between 1250-3200 m^3/h. Single blower airflow may be reliably controlled within the range of 1440-3157 m^3/h.

Pipes decrease in diameter over a distance of about 65m from blower station to diffuser systems from 0.6 to 0.2 m. The diffuser system is composed of a number of diffusers in parallel configuration located in the reactor bottom floor and connected through a network of secondary pipes to the collector-diffuser pipe. The diffusers are of membrane disk type. There are 616 and 600 diffusers in the diffuser systems 1 and 2, respectively. The diffusers are described by the nonlinear relationship between airflow and pressure drop across. In order to maintain the diffuser open, the pressure drop across the diffuser should not drop below 2 kPa (Fig. 4). The diffusers are located inside the SBR (0.35 m above the bottom of the reactor) (see Fig. 5).
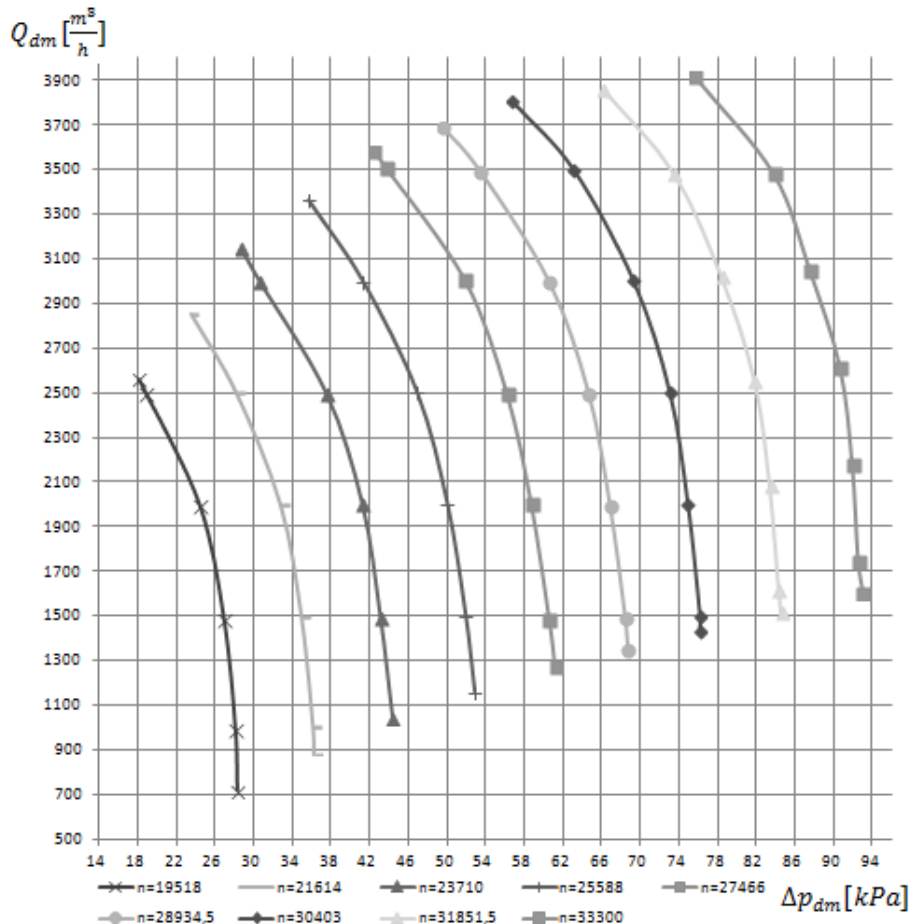

Figure 3. Relation between airflow and pressure drop across for blower [18]

3.2. Mathematical model of the aeration system

The general methodology of aeration system modelling was presented in [19]. This approach was applied for modelling different plants, e.g. Kartuzy aeration system [19-21], Nowy Dwor Gdanski aeration system [22] and Swarzewo aeration system [18, 23]. The model of the Swarzewo aeration system was first presented in [18]. The theoretical knowledge, data records from case study plant and documentation

characteristics of the system elements were used. This paper presents the above mathematical model and further research in this field.

The aeration system was modelled by treating the elements as equivalent to electrical (see Fig. 6). Airflow Q is an analog of the current, while the pressure drop across Δp is equivalent to voltage in the circuit. Blowers were modelled as current sources with nonlinear characteristics (see Fig. 3). Collector pipe was treated as a capacitor with variable capacity C_c. Collector-diffuser pipes were modelled as capacitors $C_{g,1}$ and $C_{g,2}$. Resistors $R_{g,1}$ and $R_{g,2}$ correspond to air resistances in pipes, while the $R_{d,1}$ and $R_{d,2}$ are air resistances in diffusers with nonlinear characteristic (see Fig. 4). Hydrostatic pressure in the SBR is equivalent to a voltage source.

The aeration system model was described by a set of nonlinear differential and algebraic equations. They relate to dynamics of pressure variation as a function of airflow in the collector pipe (1) and collector-diffuser pipes (2):

$$\frac{dp_c}{dt} = \frac{1}{C_c} \cdot \left(Q_b - Q_c \right) \tag{1}$$

$$\frac{d\Delta p_{d,i}}{dt} = \frac{1}{C_{g,i}} \cdot \left(Q_i - Q_{air,i} \right) = \frac{1}{C_{g,i}} \cdot$$

$$\left\{ \frac{1}{R_{g,i}} \cdot \left(p_c - \Delta p_{d,i} - \Delta p_h \right) - \frac{1}{R_{d,i}} \cdot \Delta p_{d,i} \right\},$$

$$i \in \{1, 2\} \tag{2}$$

Airflows through blowers $Q_{dm,i}$, $i \in \{1,2\}$, are nonlinear functions of pressure drop across blowers $\Delta p_{dm,i}$, $i \in \{1,2\}$, and blowers speed n_i, $i \in \{1,2\}$, is stated in (3). This function was derived from blower characteristics (see Fig. 3):

$$Q_{dm,i} = f_{dm,i} \left(\Delta p_{dm,i}, n_i \right), \quad i \in \{1, 2\}. \tag{3}$$

The airflow into the blower node Q_b can be written as:

$$Q_b = \sum_{i=1}^{2} Q_{dm,i}. \tag{4}$$

The capacitance C_c of the collector pipe is described by (5), while the capacitance $C_{g,i}$, $i \in \{1,2\}$, of the collector-diffuser pipes by (6):

$$C_c = \frac{1000 \cdot V_c}{R_m \cdot T_c} \quad \wedge \quad V_c = \frac{\pi \cdot d_c^2}{4} \cdot l_c \tag{5}$$

$$C_{g,i} = \frac{1000 \cdot V_{g,i}}{R_m \cdot T_{g,i}} \quad \wedge \quad V_{g,i} = \frac{\pi \cdot d_{g,i}^2}{4} \cdot l_{g,i}, \quad i \in \{1, 2\}, \tag{6}$$

where V_c, T_c, $R_m = 8.314472$ J/mol*K, d_c, l_c represent: volume, temperature, gas constant, diameter and length in case of collector pipe, while $V_{g,i}$, $T_{g,i}$, R_m, $d_{g,i}$, $d_{g,i}$ in case of collector-diffuser pipes.
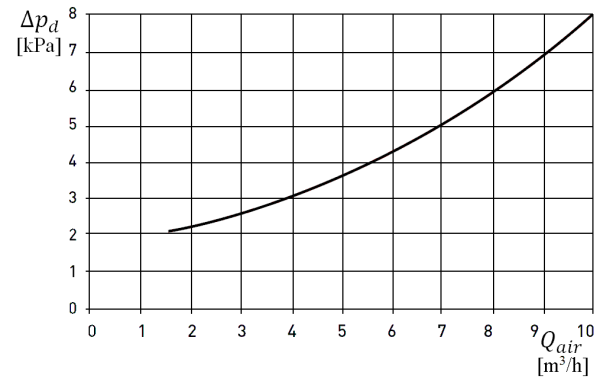

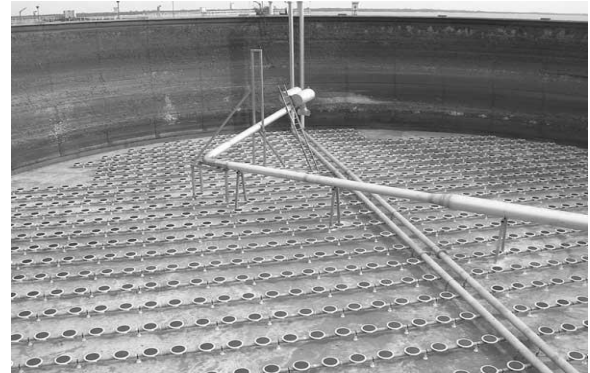**Figure 4.** Characteristic of the diffusers [18]

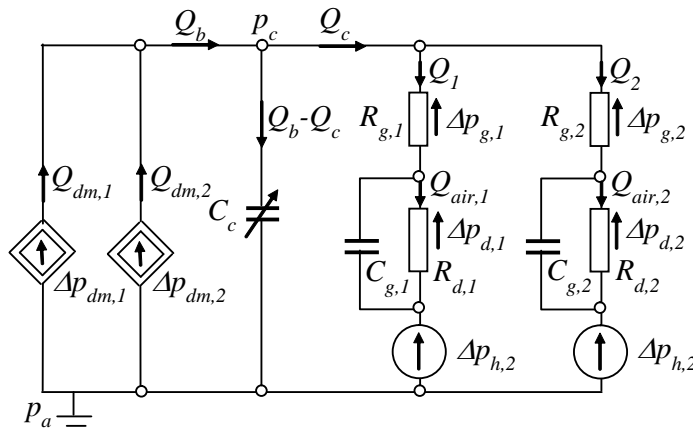**Figure 5.** Location of the diffusers in SBR 4 [18]

Figure 6. Aeration system at Swarzewo WWTP – electrical analogy (model A)

The volume $V_{g,i}$, $i \in \{1,2\}$, is expressed as an equivalent pipe volume with diameter $d_{g,i}$ and length $l_{g,i}$. The pipes have the following dimensions [18]: d_c=0.6 m; l_c=44 m; $d_{g,1}$= $d_{g,2}$=0.1 m; $l_{g,1}$=$l_{g,2}$=417 m. Due to the very small number of temperature measurements taken in the pipes a constant is assumed T_c =$T_{g,1}$=$T_{g,2}$=293 K.

Based on the real data records it was found that [18]:

$$\Delta p_{g,1} = 8.664816 \cdot 10^{-9} \cdot Q_1^2 \Rightarrow$$

$$Q_1 = \sqrt{1.15409 \cdot 10^8 \cdot \Delta p_{g,1}} \qquad (7a)$$

$$\Delta p_{g,2} = 1.216792 \cdot 10^{-8} \cdot Q_2^2 \Rightarrow$$

$$Q_2 = \sqrt{8.21833 \cdot 10^7 \cdot \Delta p_{g,2}} . \qquad (7b)$$

In a real system, pressure drop across $\Delta p_{g,i}$, $i \in \{1,2\}$, could not be a negative value. Furthermore,

even small changes in this quantity oscillating around zero cause very large changes of airflow Q_i, $i \in \{1,2\}$. Thus, equations (7a)-(7b) were approximated by a set of linear functions at a distance of 5 Pa (see Fig. 7).

Nonlinear characteristic of diffusers (see Fig. 4) is linearized based on a standard linear regression:

$$\Delta p_{d,i} = 0.47 \cdot Q_{air,i} + 1.31, \quad i \in \{1,2\}. \qquad (8)$$

The hydrostatic pressure $\Delta p_{h,i}$, $i \in \{1,2\}$, occurs at the bottom of the reactor (diffusers are located 0.35 m above the bottom of the reactor – see Figure 5). This variable depends on level of wastewater h_i, $i \in \{1,2\}$, density of wastewater ρ_s=1150 kg/m³, gravity acceleration g=9.81 m/s² and pressure drop across opening diffusers $\Delta p_{d,i}^{open}$=2 kPa, $i \in \{1,2\}$:
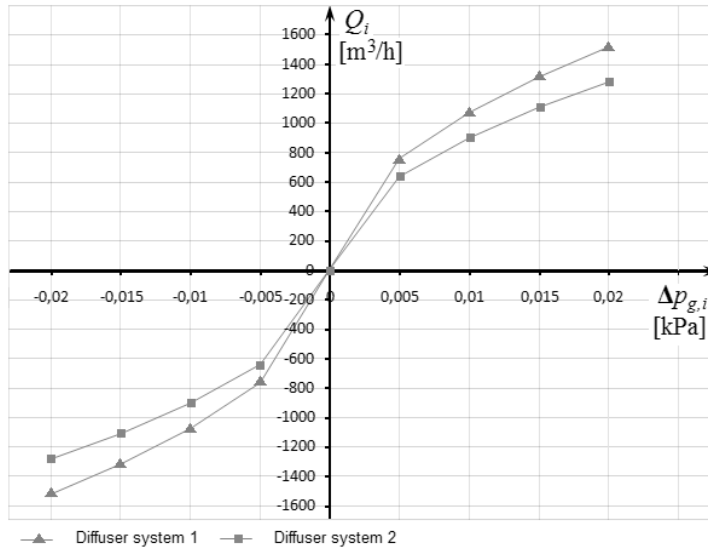
$$\Delta p_{h,i} = \begin{cases} (h_i - 0.35) \cdot \rho_s \cdot g \cdot 10^{-3} + \Delta p_{d,i}^{open} & \text{for } h_i > 0.35\,m \\ \Delta p_{d,i}^{open} & \text{for } h_i \le 0.35\,m \end{cases}, \quad i \in \{1,2\}. \qquad (9)$$

Figure 7. Approximation of equations (7a)-(7b) around zero
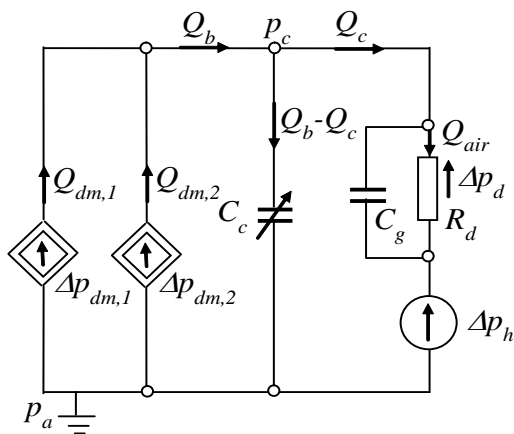

Figure 8. Modification of an aeration system model – electrical analogy (model B)

Based on real data records, temperature T_i, $i \in \{1,2\}$, is approximated as a function of pressure drop across $\Delta p_{dm,i}$, $i \in \{1,2\}$:

$$T_i = 0.92 \cdot \Delta p_{dm,i} + 281, \quad i \in \{1,2\}. \qquad (10)$$

In order to reduce the number of model parameters for identification and obtain low sensitivity to numerical errors and to increase computing efficiency with little loss of accuracy, the model has been further modified.

Quantities $R_{g,1}$ and $R_{g,2}$ are very small and have similar values (see (7a)-(7b)). Additionally, the number of diffusers is similar. Thus, there is little difference in airflow between those two diffuser systems. Therefore it was decided to replace the two diffuser systems by the combined one (Fig. 8).

Combining $C_{g,1}$ and $C_{g,2}$ we get:

$$C_g = C_{g,1} + C_{g,2} \tag{11}$$

$$Q_{air} = Q_{air,1} + Q_{air,2}$$
$$= a_d \cdot \left(k_1 \cdot \Delta p_{d,1} + k_2 \cdot \Delta p_{d,2} \right) \tag{12a}$$

$$\Delta p_{d,1} = \Delta p_{d,2} = \Delta p_d \tag{12b}$$

Hence

$$Q_{air} = a_d \cdot \left(k_1 + k_2 \right) \cdot \Delta p_d \,, \tag{13}$$

where $a_d = 0.47$, $k_1 = 616$, $k_2 = 600$ are directional factor characteristic of diffusers, the number of diffusers in the diffuser system 1 and the number of diffusers in the diffuser system 2, respectively.

$R_{g,1}$ and $R_{g,2}$ are combined and an expression is derived for diffusers resistance:

$$\frac{1}{R_d} = \frac{1}{R_{d,1}} + \frac{1}{R_{d,2}} = \frac{Q_{air}}{\Delta p_d} = a_d \cdot \left(k_1 + k_2 \right). \tag{14}$$

Others equations of the model are as follows (compare with equations (1)-(6)):

$$Q_{dm,i} = f_{dm,i}\left(\Delta p_{dm}, n_i \right), \quad i \in \{1,2\} \tag{15}$$

$$Q_b = \sum_{i=1}^{2} Q_{dm,i} \tag{16}$$

$$\frac{dp_c}{dt} = \frac{1}{C_c} \cdot \left(Q_b - Q_c \right) \tag{17}$$

$$C_c = \frac{1000 \cdot V_c}{R_m \cdot T_c} \quad \wedge \quad V_c = \frac{\pi \cdot d_c^2}{4} \cdot l_c \tag{18}$$

$$\frac{d\Delta p_d}{dt} = \frac{Q_b}{C_g + C_c} - \frac{\Delta p_d}{R_d \cdot \left(C_g + C_c \right)} \tag{19}$$

$$C_g = \frac{1000 \cdot V_{g1,2}}{R_m \cdot T_{g1,2}} \quad \wedge \quad V_{g1,2} = \frac{\pi \cdot d_g^2}{4} \cdot l_{g1,2}. \tag{20}$$

The dimensions of the pipes were calculated: d_c=0.6 m, l_c=44 m, d_g= 0.1 m, l_g= 834 m. Due to the very small number of temperature measurements taken in the pipes a constant was assumed T_c=$T_{g1,2}$=293 K.

Finally, the nonlinear model was described by differential and algebraic equations (11)-(20).

Model B of aeration system was implemented in the Matlab environment and was verified using real data records from Swarzewo WWTP. The piecewise constant motor speed input and the corresponding steady-state responses were recorded. Results of verification were promising. The maximum pressure residuum was around 2%, while the maximum airflow residuum was about 7%. Also, static characteristic $Q_{air}=f(n)$ was compared with taken measurements (Fig. 9). Satisfactory accuracy was obtained.

One of the criteria for evaluating the model was to obtain low sensitivity to numerical errors which directly influence computing efficiency. Fig. 10 (see Model A) shows fluctuations of airflow, which should not occur. The airflow changes within a very small range, however it affects the integral step in variable-step algorithm. This leads to significantly longer simulation time. Moreover, it complicates selection of an appropriate numerical algorithm for solving the model. Note that this phenomenon does not occur in the Model B (see Fig. 10).

In summary, good verification results of model B were observed. The model B was used in the next section to design the new control system.
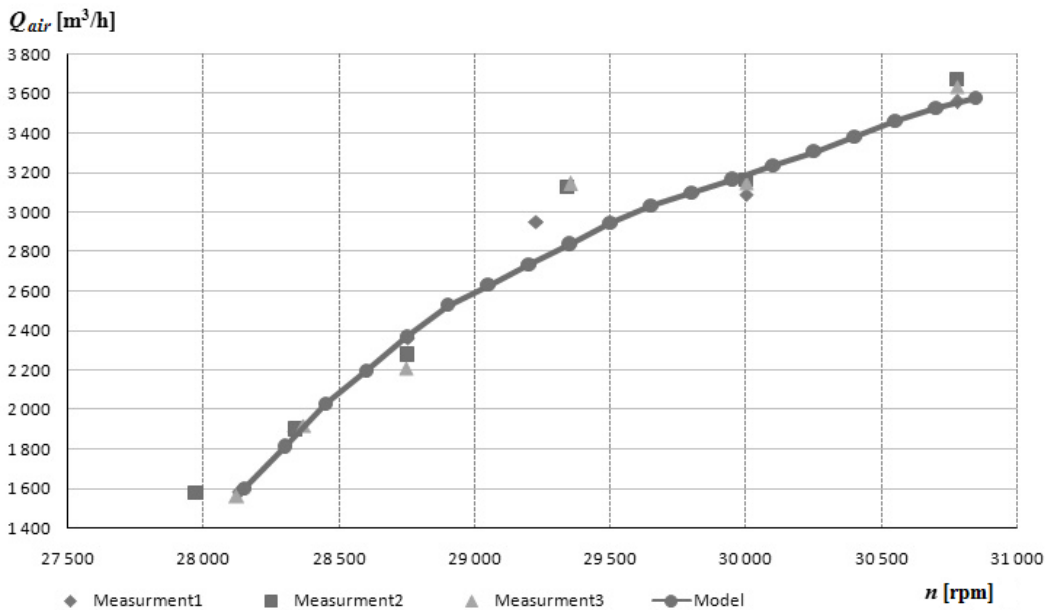
Figure 9. Comparison of the static characteristic of the model and measurements
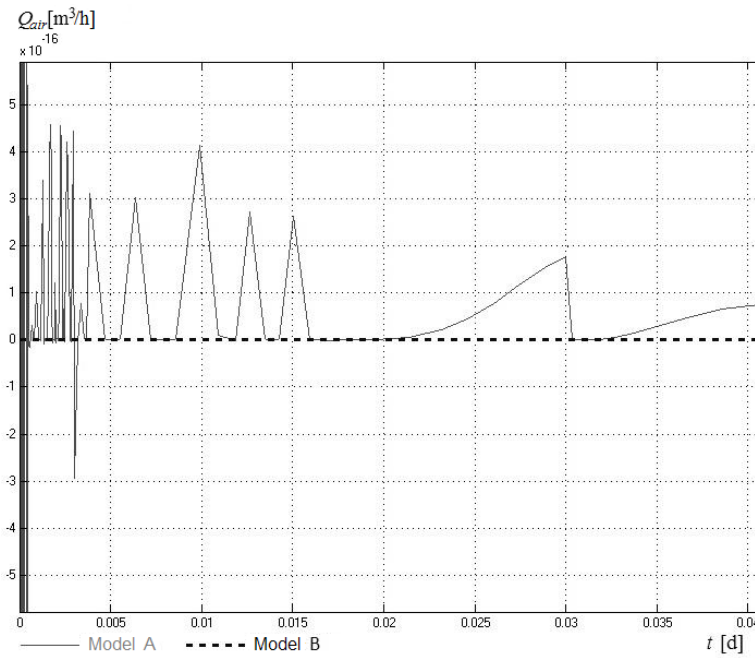
Figure 10. Comparison of the airflows: model A and B

4. Control system design

In industrial practice, mostly simple control methods are used to control DO concentration. Control technologies include manual control, rule based control and simple PLC techniques with classical PI controllers. Similar technologies (PI and rule based control) are used at Swarzewo WWTP. The DO dynamics and aeration system are nonlinear and good control performance across all the operating conditions cannot be expected to be achieved with a conventional linear controller. The structure of a new DO control system is presented in Fig. 11.
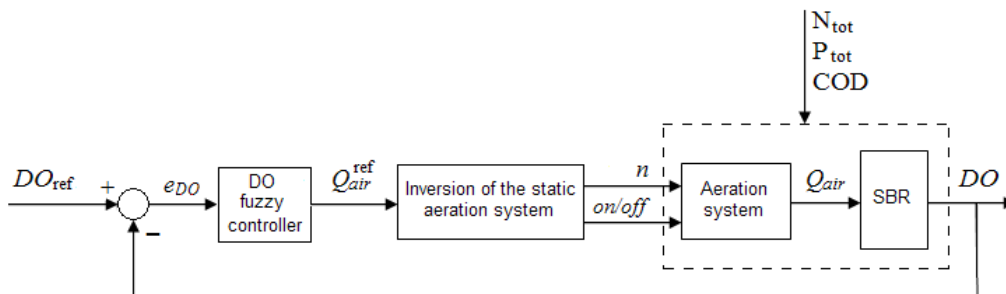

Figure 11. Structure of new control system

The controller objective is to force *DO* in the SBR to follow the prescribed reference trajectory *DO_ref*. For this reason, the control system has to provide the proper amount of air - *Q_air*. Air is then distributed into SBR by an aeration system (see Section 3). Desired airflow may be obtained by controlling blowers speed *n* and determining when to activate/deactivate blowers. The difference between *DO* and *DO_ref* involves the input to the controller. The aeration system is coupled with SBR. The variable that links *n* with the *DO* is the *Q_air* appearing in both models. The *COD*, *N_tot* and *P_tot* are disturbing input signals.

It was decided to design a nonlinear fuzzy controller with Internal Model Control (IMC) structure. The concept of IMC was first formalized by Garcia and Morari [24] and can be applied to nonlinear and multivariable systems. IMC can theoretically provide perfect control by obtaining a model of the plant and then using the inverse of this model. If a perfect model is available, the control system will achieve exact set point control despite unmeasured disturbances acting upon the process [25].

Control plant consist of two parts (aeration system and biological processes in SBR) with different dynamics. Aeration system is characterized by fast dynamics (seconds). On the other hand, the biological reactions are more slowly (hours). The dynamics of these parts were determined by calculating the time step response. The desired speed of blowers *n* and airflow *Q_air* was very quickly obtained. Moreover, the dynamics of the aeration system slightly affected over control of DO. Hence, an inverse model of the static

aeration system was used to design the control system. There is no need to build an airflow controller because the reference airflow Q_{air}^{ref} is obtained by calculating speed of blowers n and on/off switching of the blowers.

An important aspect of IMC structure is static characteristics of blowers, which had to be inversed in order to achieve desired relationship between the rotational speed of blowers and their airflow. The blower station consists of two identical blowers (see Section 3). Static characteristics of aeration system were uniquely defined for Q_{air}^{ref} (see Fig. 12). Hence, this model is reversible [25]. Combined characteristics of the two blowers are not uniformly determined, or are not determined at all in some operating points, especially for pressures above 83k Pa. However, for safety reasons pressure in the system never reaches the value of 83 kPa (see Fig. 12).
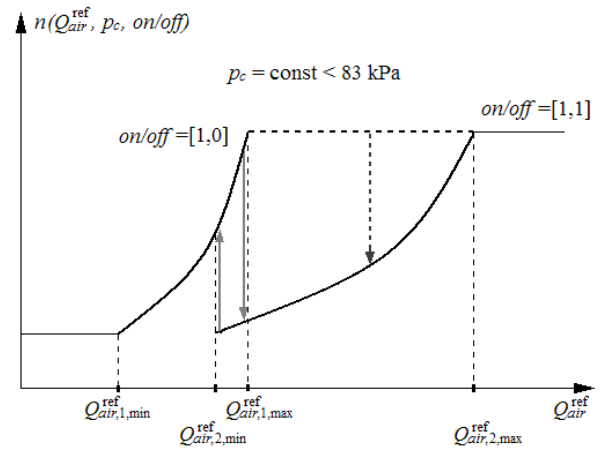

Figure 12. Static characteristics of inverse model of aeration system
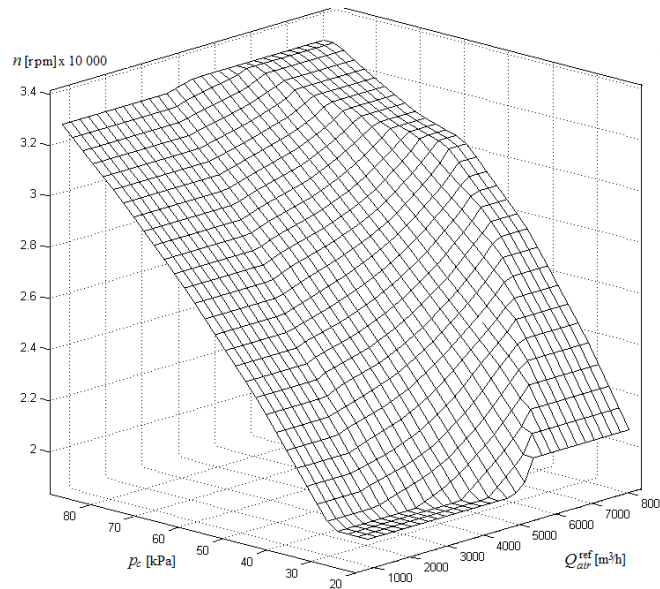

Figure 13. Surface transformation of static characteristic for two blowers

Inversion of this model requires transition between the modes: one blower activated and two blowers activated. The system uses transition with hysteresis. The model was inversed by dividing the pressure range p_c (from 20 to 90 kPa) and blower speed n (from 19518 to 33000 rpm) into 31 measuring points. For each point, airflow Q_{air}^{ref} was calculated. In that way, airflow of 961 values for each of the two cases of blower operation mode was determined. Hence it was possible to do calculations for a given pressure across the entire flow range with 30 subranges. Finding a range that contains the Q_{air}^{ref} for a given range is not particularly challenging.

The reference airflow Q_{air}^{ref} and the pressure in the pipeline p_c were input signals to the inversion model, output signal – blowers speed n and the signal determining blower activation/deactivation – on/off. Because blowers are highly dependent on the pressure p_c, inversion was four-dimensional, and the fourth dimension was discrete and dual element. Hence, the

surface characteristics of the inversion model could be easily represented graphically (Fig. 13).

The fuzzy PI controller was designed for DO and aeration system control. Inputs to the fuzzy controller are error $e_{DO,P}$ and integral error $e_{DO,I}$. Reference to airflow Q_{air}^{ref} is the output of the controller (see Fig. 14). Linguistic values and membership functions for controller variables are illustrated in Tables 1-2. The parameters of membership functions are adjusted based on technological knowledge experience and many simulation tests carried out. Values of inputs to the fuzzy controller are calculated for fuzzification membership degrees.
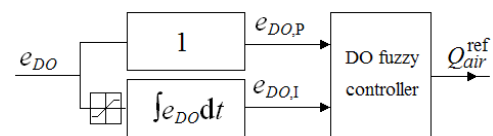

Figure 14. Scheme of DO fuzzy controller

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Table 1. Linguistic values and membership functions for the controller inputs

	Linguistic variable – error ($e_{DO,P}$)				
	Linguistic value		Membership function	Characteristic points		
1	large negative	LN	asymmetrical triangular	-0.5	-0.5	-0.1
2	average negative	AN	asymmetrical triangular	-0.5	-0.1	0
3	about zero	AZ	symmetrical triangular	-0.1	0	0.1
4	average positive	AP	asymmetrical triangular	0	0.1	0.5
5	large positive	LP	asymmetrical triangular	0.1	0.5	0.5

	Linguistic variable – integral error ($e_{DO,I}$)				
	Linguistic value		Membership function	Characteristic points		
1	large negative	LN	asymmetrical triangular	-0.4	-0.4	-0.08
2	average negative	AN	asymmetrical triangular	-0.4	-0.08	0
3	about zero	AZ	symmetrical triangular	-0.08	0	0.08
4	average positive	AP	asymmetrical triangular	0	0.08	0.4
5	large positive	LP	asymmetrical triangular	0.08	0.4	0.4

Table 2. Linguistic values and membership functions for the controller output

	Linguistic variable – reference of airflow (Qairref)			
	Linguistic value		**Membership function**	**Characteristic point**
1	minimum	Min	singleton	700
2	very small	VS		2080
3	small	S		2770
4	medium	M		4150
5	large	L		5530
6	very large	VL		6220
7	maximum	Max		7600

Rule base contains 25 rules (see Table 3), e.g.:

RB1: IF ($e_{DO,P}$ = AZ) AND ($e_{DO,I}$ = AN) THEN (Q_{ref} = S)

RB2: IF ($e_{DO,P}$ = AN) AND ($e_{DO,I}$ = AP) THEN (Q_{ref} = VS)

RB3: IF ($e_{DO,P}$ = AP) AND ($e_{DO,I}$ = LP) THEN (Q_{ref} = Max)

Sample membership values for inputs are presented in Table 4.

Table 3. Rule base of the fuzzy controller

Inputs	**Linguistic variable**	**Integral error ($e_{DO,I}$)**				
	Linguistic value	LN	AN	AZ	AP	LP
	LN	Min	Min	Min	Min	Min
	AN	Min	VS	VS	VS	VS
error ($e_{DO,P}$)	AZ	Min	S	M	L	Max
	AP	VL	VL	VL	VL	Max
	LP	Max	Max	Max	Max	Max

Table 4. Example membership values for inputs

Linguistic variable	**Error ($e_{DO,P}$)**					**Integral error ($e_{DO,I}$)**				
Linguistic value	LN	AN	AZ	AP	LP	LN	AN	AZ	AP	LP
$\mu(\cdot)$	0	0.3	0.7	0	0	0	0	0.2	0.8	0

Determining the degree of fulfillment of the conditions is calculated as follows:

$$\mu_R\left(e_{DO,P}, e_{DO,I}\right) = PROD\left\{\mu\left(e_{DO,P}\right), \mu\left(e_{DO,I}\right)\right\} \quad (21)$$

Therefore, a modified set of μR conclusions for all rules was obtained (Table 5).

The defuzzification process converts variables into physical ones. Different kinds of defuzzification methods, like the center of area method, the fuzzy mean method, the maxima method or height method, are being researched. The last of those techniques was applied (see (22) and Table 6).

$$Q_{ref} = \frac{\sum_{j=1}^{25} Q_{air,j}^{ref} \cdot \mu\left(Q_{air,j}^{ref}\right)}{\sum_{j=1}^{25} \mu\left(Q_{air,j}^{ref}\right)} \quad (22)$$

Table 5. The degree of fulfillment of the conditions – inputs

Variable			Integral error ($e_{DO,I}$)			
	μ(·)	0	0	0.2	0.8	0
	0	0	0	0	0	0
	0.3	0	0	0.06	0.24	0
error ($e_{DO,P}$)	0.7	0	0	0.14	0.56	0
	0	0	0	0	0	0
	0	0	0	0	0	0

μR($e_{DO,P}$, $e_{DO,I}$)

Table 6. The degree of fulfillment of the conditions – output

Linguistic variable	Reference of airflow (Q_{air}^{ref})						
Linguistic value	Min	VS	S	M	L	VL	Max
Numerical value	700	2080	2770	4150	5530	6220	7600
μ(Q_{air}^{ref})	0	0.3	0	0.14	0.56	0	0

A detailed diagram of the DO fuzzy controller and control surface is illustrated in Fig. 15-16.
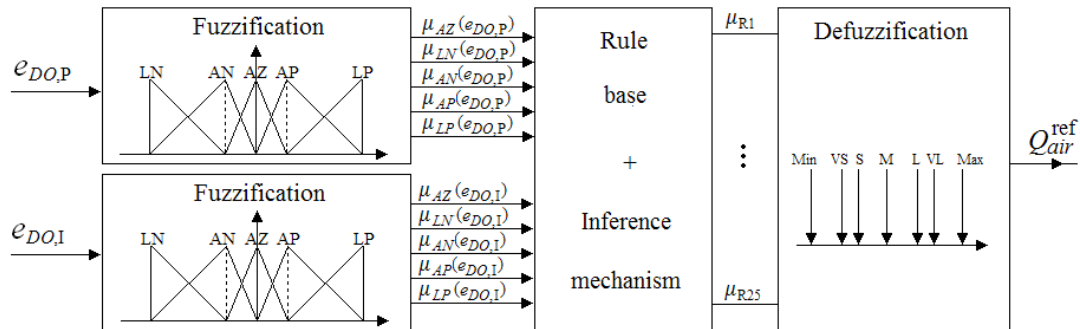

Figure 15. Detailed diagram of the DO fuzzy controller

5. Simulation results

This section describes the proposed control strategy (see Section 4) being tested by simulation using real data records from Swarzewo WWTP. The commercial simulation package Simba [26] was used to model the SBR. The model of an aeration system was implemented in the Matlab environment. Next, both models were connected. Matlab suite was used to implement the nonlinear fuzzy controller.

Basic assumptions of simulation tests were as follows: wastewater temperature in SBR and air temperature are equal to 15°C, the rate of SBR filing is 100 000 m³/d, rate of decantation is 50 000 m³/d, speed of excess sludge removal is 8 000 m³/d, filling of the reactor was chosen experimentally and was constant for all cycles of the study. Conditions for transition to the next phase of a SBR are illustrated in Table 7

The COD, N_{tot} and P_{tot} are the parameters (disturbances) describing the influent sewage composition. The experiments correspond to real data sourced during case study plant operation and from disturbances. Control results for two different scenarios are illustrated. Those scenarios are
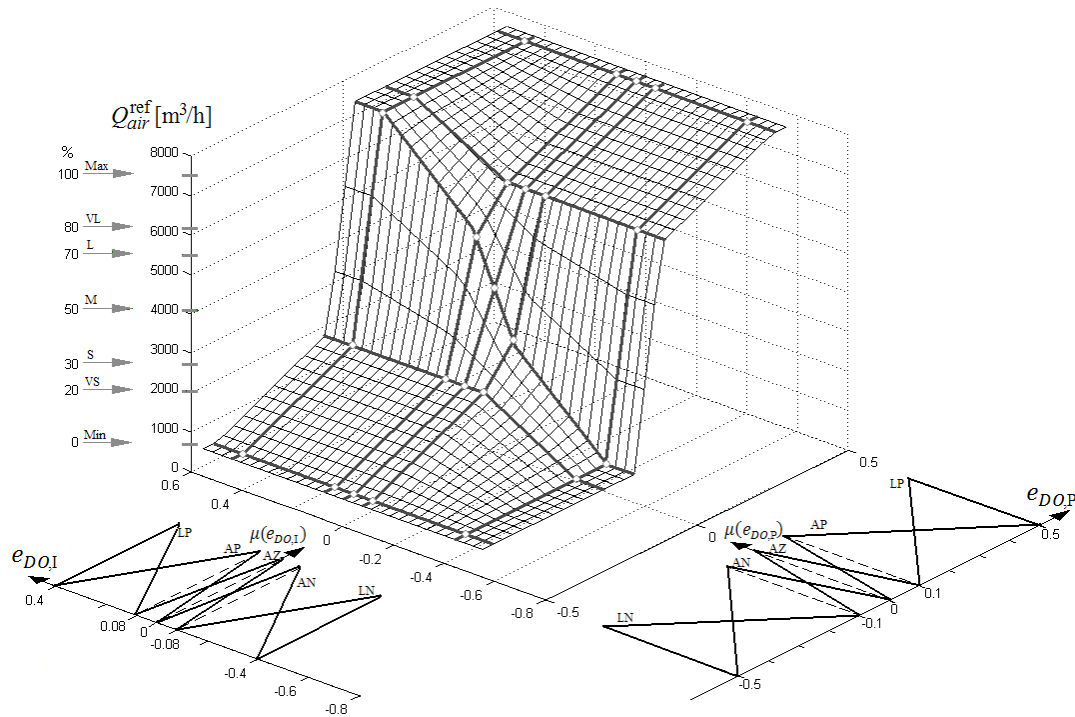
Figure 16. Control surface of DO fuzzy controller

Table 7. Conditions for the transition to the next phase in a single cycle of a SBR

Phase i	Phase i+1	Condition of phase transition
Filling	Denitrification	$V_s \geq V_{s,max}$
Denitrification	Nitrification	$NO_3 + NO_2 < 0.2$ mg/dm^3
Nitrification	Sedimentation	$NH_4 < 0.8$ mg/dm^3
Sedimentation	Decantation	after 80 min
Decantation	Removal of excess sludge	$V_s \leq V_{s,min}$
Removal of excess sludge	Filling	after 30 s

where $V_{s,max}$, $V_{s,min}$ are the amount of wastewater after filling of the reactor and the amount of wastewater after decantation of the reactor, respectively.

Table 8. Parameters of influent sewage and SBR

Parameter	Case 1	Case 2
COD [mg/dm^3]	377	1074
N$_{tot}$ [mg N/dm^3]	45	110.3
P$_{tot}$ [mg P/dm^3]	7.1	14.7
V$_{s,min}$ [m^3]	3200	
V$_{s,max}$ [m^3]	4200	
DO$_{ref}$ [mg O$_2$/dm^3]	2	

representative of different biological conditions of the plant. Parameters of influent sewage and a SBR used in these studies are presented in Table 8. At the input to the plant is retention tank, in which the influent sewage is mixed and then sewage is provided to SBR. Hence, the disturbance values are always constant.

As the first, the classical PI control system was tested. The efficiency of PI controller was poor: long settling time, large overshoot, nonzero steady state error and the frequent changes of blower speed and blower switching (on/off). The system is nonlinear, and good control performance for all the operating conditions cannot be obtained with a linear PI controller with fixed parameters.

Figs. 17-18 present control results for fuzzy control system.

Good tracking performance was observed for different conditions. One blower is able to meet the air demand Q_{air} most of the time (Fig. 17) given low concentrations of pollutants (Case 1). Once one of the blowers is deactivated it results in *DO* and Q_{air} fluctuations. When a concentration of pollutants is high (Case 2) there is a need to use both the blowers (Fig. 18). Blower operation depends on the trajectories of *DO* and concentration of pollutants. The wide range
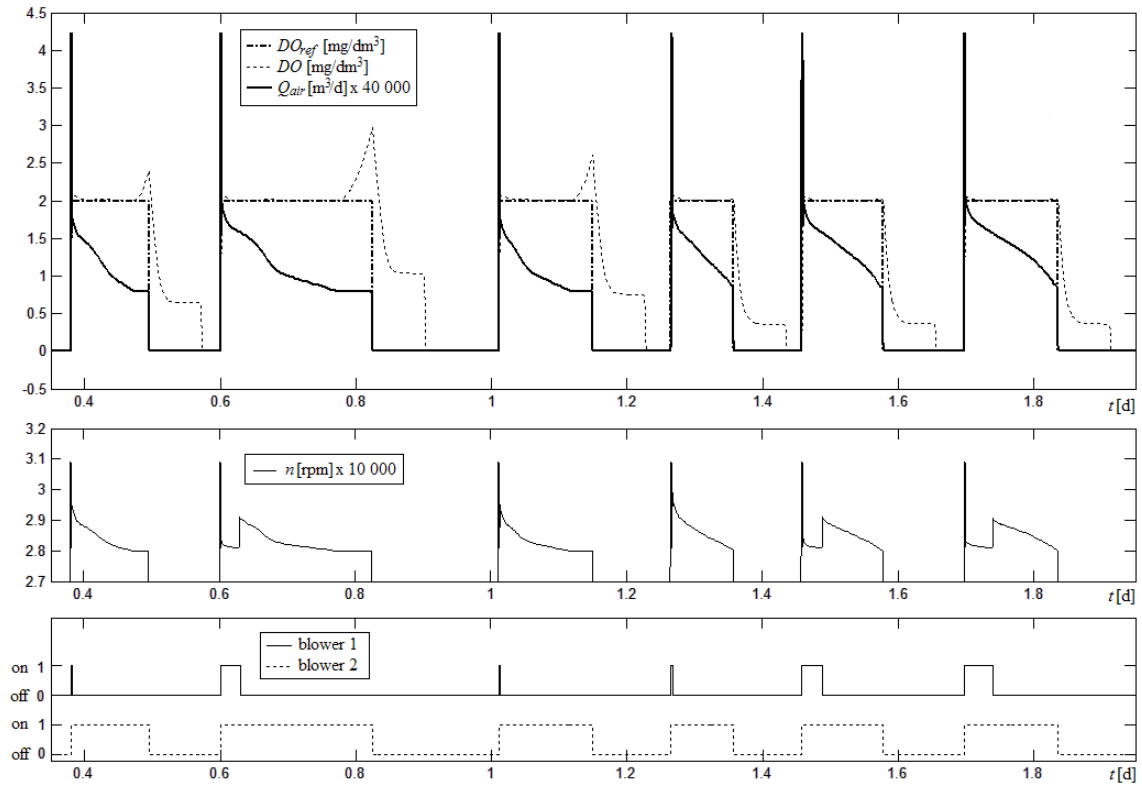
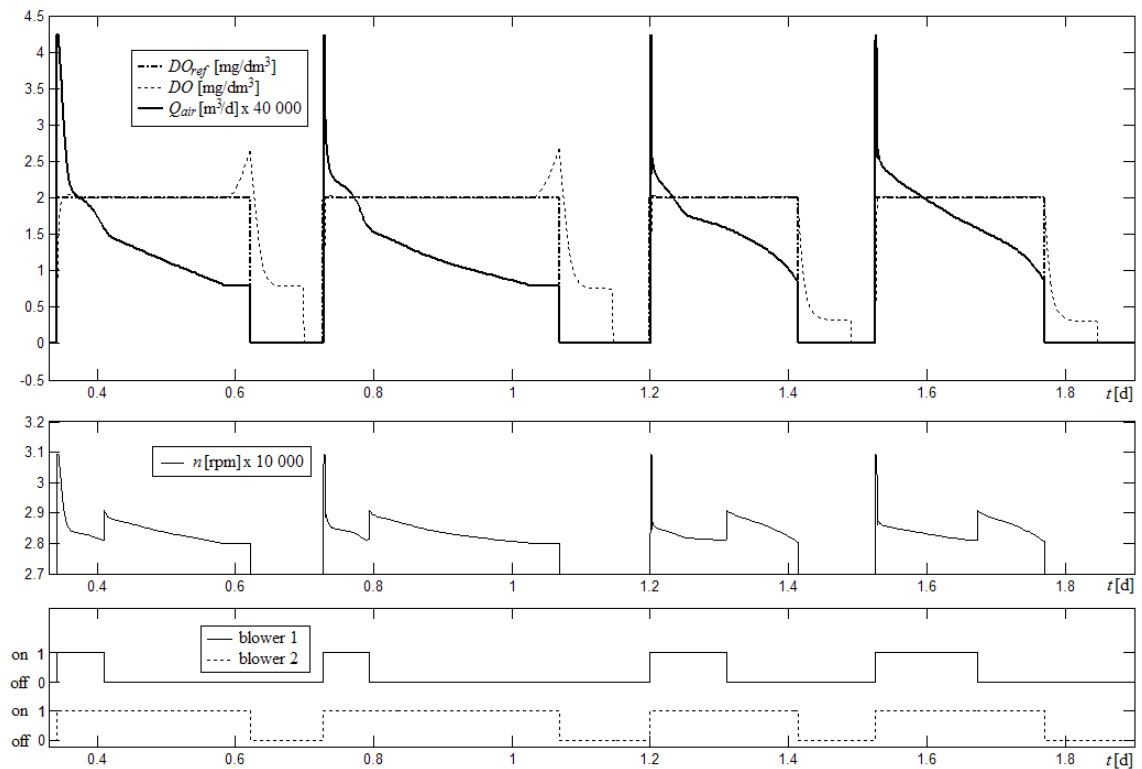**Figure 17.** Control results for fuzzy control system – Case 1

Figure 18. Control results for fuzzy control system – Case 2

of variable speed the blower is operating at is affected by a small number of gear changes for the fixed speed blowers.

The results also indicate it is possible to set a DO trajectory that would enable reaching the desired compromise between energy consumption, time of aeration and the quality of treated wastewater. Also, there are situations where the blowers run at minimum power. The demand for oxygen is so small that less air is required than activated, running at minimum power

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blowers provide. This may indicate the need to modify the aeration system by installing less powerful blowers.

The control actions generated by actuating devices (blowers) are different for different disturbances (see Table 8) but quality of control system is similar (see Figs. 17-18).

In summary, the results of DO control, for different conditions, are not optimal (optimization methods have not been used). However, advanced control algorithms (i.e. fuzzy control system) significantly improve the control quality in comparison with the control results obtained by using a classical PI controller. The fuzzy control system is characterized by shorter settling time, much smaller overshoot and steady state error equal zero. Moreover, the fuzzy control system significantly improves the utilization of actuating devices (blowers switching (on/off)).

6. Conclusions

This paper addressed tracking reference trajectory of dissolved oxygen concentration in a wastewater treatment plant. A sequencing batch reactor was considered. A centralised fuzzy controller was derived. An aeration system was included in the overall controller design. Its properties and tracking performance were investigated by simulation using real data records from Swarzewo case study plant. Good tracking performance of dissolved oxygen was obtained. The aeration system provided the required amount of airflow. Promising results were achieved.

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