# OXYGEN TRANSFER PROCESS SIMULATION IN WASTEWATER AERATION TANK

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**Abstract**. The research paper discusses oxygen transfer process in wastewater biological treatment system, and provides mathematical model and simulation of steady state oxygen transfer from supplied air to the activated sludge in wastewater aeration tank. Wastewater aeration is one of the most important components of the biological treatment process from energy point of view because of large energy consumption and need for non-stop operations. Thus, the process of oxygen transfer is not only technical, but also economic matter of great importance, and must been considered as a main factor of optimization. In order to observe this process the mathematical model of aeration tank as a non-linear control object with variable sensitivity and response inertia indicators is been compiled. Oxygen transfer process was simulated, using Matlab "Simulink" technology, taking in account the impact of constructive parameters of aeration unit and randomly fluctuating perturbations – wastewater afflux and biological oxygen need on the control variable – oxygen concentration. Simulation model will enable to design the adaptive invariant control system for optimal wastewater aeration.

**Key words**: wastewater, aeration tank, oxygen concentration, control, mathematical modelling, simulation.

## Introduction

Wastewater biological treatment systems (WBTS) require uninterruptible and sufficient air oxygen supply to the aeration tanks by wastewater aeration units in order to supply the microbes in the activated sludge with necessary amount of oxygen. Aeration system consists of the wastewater aeration tank and air distribution unit with atmospheric air diffusers for unified and equal air distribution within the wastewater and activated sludge, and air blowers with frequency controlled electrical drives. Optimal control of air blowers and choice of appropriate constructive and technological parameters of air distribution unit and wastewater aeration tank are very important for electric energy saving and for improvement of process quality and economic indices [1, 2, 3].

Research made previously proves that wastewater aeration tank is a non-linear object with variable steady state parameters and variable indicators of sensitivity and response inertia [4, 5, 6]. Thus, the dynamics of oxygen transfer process and impact of perturbations may be described by non-linear differential equations with variable coefficients as the functions of time. The analysis of dynamic processes within so complicated system is very serious problem [7, 8]. In order to reduce complexity of analysis process, simplified linear model appropriate for limited scope of parameters and operations is been used, where the static and dynamic parameters (static gain and time constant) of the control object – aeration tank are considered as the constant values [9, 10, 11]. At the same time this linear model creates substantial control error when the variable parameters pass over the values stated in this simplified control set.

Using Matlab "Simulink" technology for simulation of oxygen transfer allows to simulate a non-linear object and enables to adapt the control variable – oxygen concentration to the constructive parameters of wastewater aeration unit and randomly fluctuating wastewater afflux and biological oxygen need.

The main task of this work is to compile the mathematical model and create the block diagram for the oxygen transfer process simulation in the wastewater aeration tank, which enables to adapt the static parameters of the aeration tank to the variable perturbations.

## Research object and methods

Research object is the wastewater aeration system. The variable gains and perturbations for the aeration tank are calculated to take into account the main parameters of input wastewater, as well as constructive and technological parameters of the aeration tank, the air distribution unit and the air blower. For mathematical modeling and composition of simulation block-diagram the Laplace transforms, Matlab functions, "Simulink" library and the automatic control theory elements are used [9, 10, 12]. Research performed previously enables to create quasi empirical equations and mathematical expressions which allow to present the principles of interconnection between oxygen utilization, capacity of air blower and parameters of wastewater distribution unit [4, 5].

**Mathematical model for simulation**

In order to provide full analysis of wastewater aeration control system (WACS), the simulation model with both static and dynamic characteristics included must be created. Static model for activated sludge wastewater biological treatment describes oxygen transfer in the aeration tank, taking in account activated sludge re-circulation, and using concentration of dissolved oxygen as a control parameter. The main task of current research was to find out how the dissolved oxygen concentration $C$, capacity of air blower $L_g$ and wastewater and aeration system parameters correlate. Using research results, the following formula can be obtained:

$$C = C_S(T,h) - \frac{q \cdot K_1(h,\lambda_d,\sigma_s)}{L_g \cdot K_2(T,h)}, \tag{1}$$

where $C_s(T,h)$ – oxygen solubility in water, g/m$^3$;
$T$ – wastewater temperature, $^{o}$C;
$h$ – wastewater aeration diffuser submerging depth, m;
$q$ – oxygen consumption for wastewater purification as a load, g/min;
$L_g$ – air capacity supplied to aeration tank, m$^3$/min;
$K_1(h,\lambda_d,\sigma_s)$ – correction coefficient taking in account the constructive parameters of the aeration system;
$K_2(T,h)$ – correction coefficient taking in account impact from activated sludge to the aeration process.

Oxygen solubility depends on the wastewater temperature $T$ and aerator diffuser submerging depth $h$. It can be described using non-linear equation:

$$C_S(T,h) = \left(0.0025 \cdot T^2 - 0.3 \cdot T + 14.2\right) \cdot \left(1 + 0.05 \cdot h\right). \tag{2}$$

Correction coefficient taking in account the constructive parameters of the aeration system can be calculated using the following formula:

$$K_1(h,\lambda_d,\sigma_s) = \exp\left[-\lambda_d \cdot \left(0.11 - 0.008 \cdot h\right) \cdot \exp\left(-2.2 \cdot \sigma_s\right)\right], \tag{3}$$

where $\lambda_d$ – air flow intensity through one disk diffuser, m$^3$/min;
$\sigma_s$ – density of disk diffusers on the aeration tank floor area.

Air flow intensity through one disk diffuser $\lambda_d$ depends on constructive parameters of the aeration tank, and rated biological oxygen need (BON) for complete wastewater purification:

$$\lambda_d = \frac{L_g}{n_d \cdot S_a}, \tag{4}$$

where $n_d$ – number of disk diffusers per one square meter of aeration tank surface, m$^{-2}$;
$S_a$ – area of aeration tank surface, m$^2$.

Density of disk diffusers on the aeration tank floor $\sigma_s$ can be calculated using the formula:

$$\sigma_s = n_d \cdot S_d, \tag{5}$$

where $S_d$ – area of air diffuser surface, m$^2$.

Correction coefficient $K_2(T,h)$ depends on the wastewater temperature and air diffusers submerging depth:

$$K_2(T,h) = 5.8 \cdot \left[1 - \exp\left(-0.1 \cdot h\right)\right] \cdot \left(0.02 \cdot T + 0.6\right). \tag{6}$$

The wastewater aeration tank mathematical model development is based on the superposition principle, where each variable parameter consists of two parts – the static value, which shows rated value of the parameter, and the dynamic component, which changes over the time. The particular value of dynamic component at particular time can be either positive or negative – it either increase or decrease the summarized value.

Using superposition principle, oxygen concentration $C$ and oxygen consumption $q$ is redesigned as a sum of two components – static and dynamic:

$$C = C_0 \pm \Delta C \tag{7}$$

and

$$q = q_0 \pm \Delta q \ . \tag{8}$$

The static and the dynamic components of biological oxygen consumption $q$ are composed of two parameters – the wastewater afflux and the biological oxygen need:

$$q_0 = Q_0 \cdot L_r \tag{9}$$

and

$$\Delta q = \Delta Q \cdot L_r \ , \tag{10}$$

where $Q_0$ – wastewater afflux, $m^3$/min;
$\Delta Q$ – wastewater afflux variation, $m^3$/min;
$L_r$ – rated biological oxygen need (BON) for complete wastewater purification, $g/m^3$.

At the current development stage of wastewater parameters control and measurement technologies can not offer appropriate instant wastewater BON measuring technology usable for automatic control systems. As $L_r$ changes slowly and insignificantly, aeration tank static performance modelling allows us to consider that $L_r$ = const.

Biological oxygen need depends directly on the wastewater composition – amount of organic substances, ammonia, phosphorus, etc. Research shows that this parameter has very stable daily and weakly seasonality trends, especially the ammonia content in the wastewater [8]. At the same time we can state that for particular periods of time in the day these parameters practically do not change. This applies also to the temperature of wastewater – it does not have significant changes, so it was considered to assume that $T = T_0$ = const.

If particular aeration tank load is known, formula (1) changes:

$$C_0 = C_S(T_0, h) - \frac{q_0 \cdot K_1(h, \lambda_d, \sigma_s)}{L_g \cdot K_2(T_0, h)} \ . \tag{11}$$

Impact of load perturbation on the oxygen concentration change can be calculated using the following formula:

$$\Delta C = \pm \frac{\Delta q \cdot K_1(h, \lambda_d, \sigma_s)}{L_g \cdot K_2(T_0, h)} . \tag{12}$$

The static gain of the aeration tank $K_a$ can been expressed calculated:

$$K_a = \frac{C_0}{L_g} = \frac{C_S(T_0, h)}{L_g} - \frac{q_0 \cdot K_1(h, \lambda_d, \sigma_s)}{L_g^{\ 2} \cdot K_2(T_0, h)} \ . \tag{13}$$

Formula (13) shows that the static gain of the aeration tank $K_a$ depends on the two variables – the load perturbation $q_0$ and the control input impact parameter $L_g$. Thus the aeration tank is non-linear non-stationary control object with variable sensitivity.

Static gain for the load impact on oxygen concentration can been calculated using formula:

$$K_q = \frac{\Delta C}{\Delta q} = \frac{K_1(h, \lambda_d, \sigma_s)}{L_g \cdot K_2(T_0, h)} \ . \tag{14}$$

Formula (14) shows that $K_q$ is variable depending on the value of control impact $L_g$, thus it will been adjusted to variable $L_g$. Sensitivity of the control object to the perturbation $q$ decreases with increase of control impact $L_g$.

## Data for simulation

For the simulation of the wastewater aeration process, the data of the real small scale wastewater biological treatment system (WBTS) are used. They are the following:

- wastewater supply Q = 3.5 $m^3$/min;
- rated biological oxygen need (BON) $L_r$ = 150 g/$m^3$;
- dissolved oxygen concentration $C_0$ = 2 g/$m^3$;
- wastewater temperature $T_0$ = 15 $^oC$;
- rated air blower capacity 2400 $m^3$/h;
- wastewater aeration diffuser submerging depth h = 6 m;
- calculated air supply through one disk diffuser $\lambda_d$ = 0.025 $m^3$/min;
- number of disk diffusers on the aeration tank surface $n_d$ = 1.5 $m^{-2}$;
- density of disk diffusers on the aeration tank floor area $\sigma_s$ = 0.063.

Simulation model of aeration tank static performance is presented in the Fig. 1.

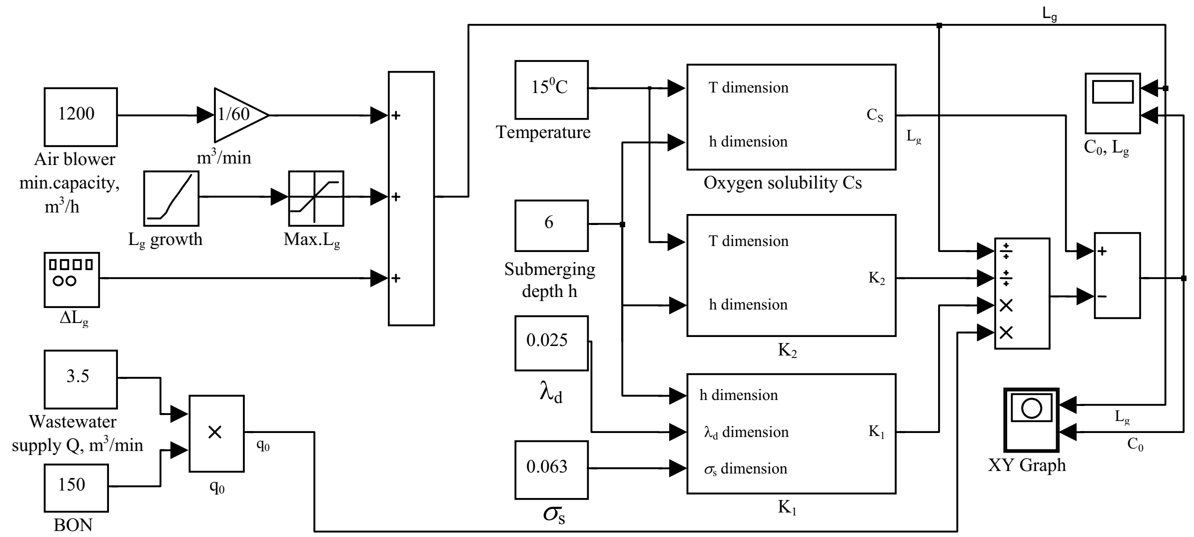


Fig. 1. **Aeration tank static performance simulation block diagram**

The simulation model is composed accordingly to the formula (11) and consists of several blocks for simulation of input impact $L_g$, oxygen consumption $q$ as a load, and constructive parameters of the wastewater aeration tank and air distribution unit ($h$, $\lambda_d$, and $\sigma_s$) as well as parameters of wastewater ($T$, $L_r$ and $Q$). Static component of oxygen consumption $q_0$ varies from 175 g/min to 700 g/min and adjustable air supply as a air blower capacity varies from 20 $m^3$/min to 40 $m^3$/min).

The simulation results of oxygen concentration $C_0$ change are presented in the Fig.2. Analysis of simulation results shows that dissolved oxygen concentration changes the same way with the change of air capacity supplied to the aeration tank. With increase of the load $q_0$ the dissolved oxygen concentration decreases. Bacteria need more oxygen, if wastewater is more concentrated. At the same time this correlation is non-linear, and depends on the load. This means that the wastewater aeration tank is non-stationary oxygen transfer object with time variable static parameters. Thus for optimal oxygen transfer process control an adaptive control system should been designed.

The simulation results of the static gain $K_a$ as the function of the variable air consumption $L_g$ under different loads $q_0$ are presented in the Fig. 3.

Analysis of the simulation results shows that the static gain $K_a$ of the aeration tank is complex and complicated variable, and it changes substantially under different loads and air blower capacities. As it can see from Fig. 3, the static gain $K_a$ changes with exponential trend, and has maximum point, which moves in order to air consumption and load.

Only within specified narrow range of $L_g$ variations $K_a$ can assume as a constant, but with change of $q$ it changes substantially.

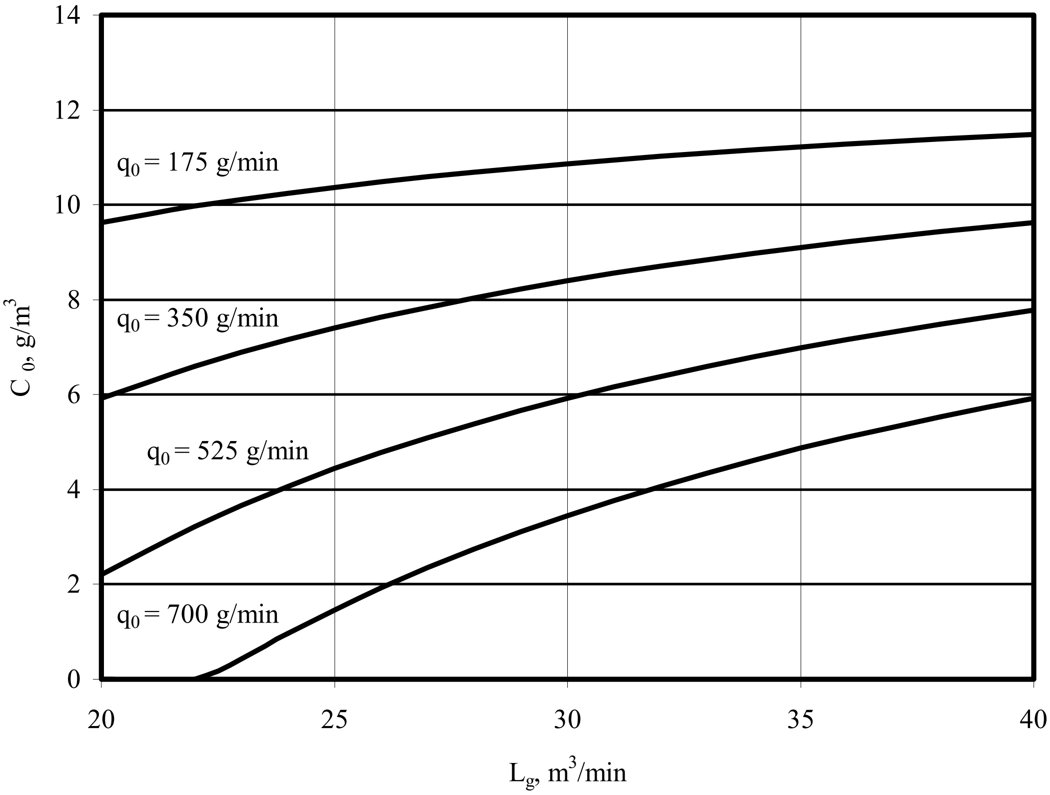


Fig. 2. **Simulated oxygen concentration $C_0$ as a function of air consumption under different loads**

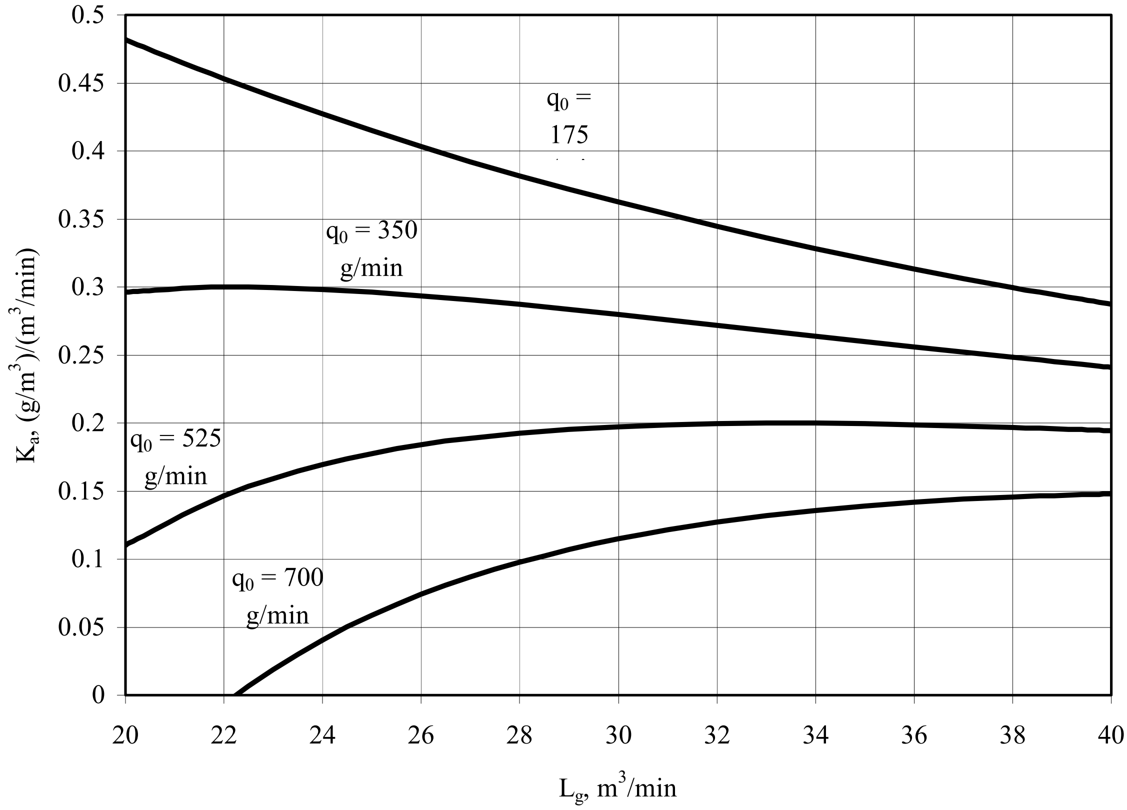


Fig. 3. **Simulated static gain $K_a$ as a function of air consumption under different loads**

## Conclusions

1. Analysis of the wastewater aeration tank static characteristics proves that it is non-linear non-stationary object with variable sensitivity. Research shows that the static gain $K_a$ of the aeration tank depends on the load $q_0$ and air blower capacity $L_g$ ($K_a = f(L_g, q_0)$) what makes it complicated to simulate and control of oxygen transfer dynamics.
2. Linearization of non-linear static characteristic $C = f(L_g, q_0)$ allows to make simplified control model for narrow load and operations range. Simultaneously such linearization introduces substantial errors when the load is out of the stated variables range, what reduces practical use of the model.
3. Simulation using Matlab functions and "Simulink" allows to create the model of wastewater aeration tank which can adopt the transfer gains adequately for oxygen concentration range under different $L_g$ and $q_0$ values. The air blower control system which will use simulated model will operate close to optimal and the air blower system designed with simulated adaptive aeration tank model will operate close to optimal.

## References


1. A. Sniders, A. Laizans. Main conditions of wastewater aeration unit design parameters, Proceedings of the International Conference "Research for Rural development", Jelgava, May 2006, pp. 160-164.
2. J. Ferrer. Energy saving in the aeration process by fuzzy logic control, Water Science Technology, 1998, Vol. 38, No. 8, pp. 209-217.
3. Шнидерс А.. Моделирование и энергоэкономное управление системой аэрации сточных вод /Труды 3-ей Международной научно практической конференции "Экология и сельскохозяйственная техника". – Санкт-Петербург: НИИМЭСХСЗ, 2002, С. 294-302.
4. A. Sniders, U. Skrastins. Identification of the aeration tank as the object of oxygen transfer under static regime, Proceedings of the Latvia Univ. of Agric., Jelgava, vol. 2 (279), 1995, pp. 79-85.
5. A. Sniders Static indices of wastewater pneumatic aeration, Proceedings of the Latvia Univ. of Agric. Jelgava, vol. (8), 1997, pp. 43-47.
6. M. Mussati, K. Gernary, R. Gani, S.A. Jorgensen. Performance analysis of denitrifying wastewater treatment plant / Clean Technology Environment Policy, Springer-Verlag, 2002, No. 4, pp. 171-182
7. Ingildsen P., Jeppsson U., Olsson G. Dissolved oxygen controller based on on-line measurements of ammonium combining feed-forward and feedback. Water Sci Technol. 2002; 45(4-5): 453-60.
8. M. Yong, P. Yongzhen, W. Shuying. Feedforward-feedback control of dissolved oxygen concentration in a predenitrification system/ Bioprocess Biosystem Engineering, Springer-Verlag, 2005, No. 27., pp. 223-228.
9. A. Sniders. Feedback & Feedforward control of wastewater aeration. Proceedings of the International Conference "Advanced technologies for energy producing and effective utilization", Jelgava, pp. 124-129, June 2004.
10. A. Šnīders, A. Laizāns. Invariant Control of Wastewater Aeration // Advances in Computer, Information, and Systems Sciences, and Engineering / Proceedings of IETA 2005, TENE 2005 and EIAE 2005 – Bridgeport USA: University of Bridgeport, Published by Springer 2006, pp. 99-103.
11. A. Šnīders. Notekūdeņu aerācijas iekārtas pārejas procesa modelēšana/ 4. Starptautiskās konferences "Vide. Tehnoloģija. Resursi" materiāli. – Rēzekne, Rēzeknes Augstskola, 26.-28.06.2003. 268.-274. lpp.
12. Carlos A. Smith, Armando B. Corripio. Principles and Practice of Automatic Process Control, 2nd ed. New York: John Willey & Sons, 1997, 768 p.