Modeling and optimizations of mixing and aeration processes in bioreactors with activated sludge

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Abstract. Mixing aimed at homogenization of the volume of bioreactors with the activated sludge is of great importance for the proper course of the wastewater treatment process. It affects both the efficiency of pollutants removal and the properties of the activated sludge related to its sedimentation. The mixing process in bioreactors can be carried out in different ways. In batch bioreactors in the aeration phase or flow bioreactors in aerobic chambers, mixing is carried out through aeration systems. These systems should aerate the activated sludge flocs for efficient biological treating of wastewater, as well as effectively homogenize the volume of the bioreactor. Hence, it is important to choose such a design of the aeration system and its operation settings that provide the amount of air ensuring the exact amount of oxygen for the implementation of technological processes, counteract sedimentation of sludge at the bottom of the reactor, are reliable as well as economical in operation (demand of electric energy). The paper presents the model studies aimed at optimization of the design and settings of aerations and mixing systems used in active sludge bioreactors.

1. Introduction

With its accession to the European Union, Poland has committed itself to meeting the requirements for introducing new or adapting the existing legislation in many areas, including wastewater management. One of the most important sources of EU law regulating the conditions of wastewater treatment is the Council Directive 91/271/EEC concerning urban wastewater treatment, called the Wastewater Directive [1]. Among the other things, the directive requires the member countries to ensure wastewater treatment with an increased standard of removal of biogenic compounds. This made it necessary to intensify the efforts to upgrade the existing municipal wastewater treatment plants in the country and to implement modern technologies in this sector of the economy, especially the technologies based on biological methods [2–7]. In the systems with integrated removal of nutrients and carbon compounds, treatment processes are carried out under the anaerobic, anoxic and aerobic conditions. Therefore, the adequate
Aeration of activated sludge is of great importance, which, however, is also one of the most energy-intensive processes in wastewater treatment plants [2,3,8]. Thus, research is largely focused on the search for more and more advanced solutions characterized by high energy efficiency, to ensure the required standards of wastewater treatment on the one hand, and to promote the reduction of operating costs on the other. At the same time, the technological trends strive to increase the reliability of equipment, which determines the use of innovative working methods in the design and construction of new technical solutions [9].

One of the technologies using the activated sludge methods is the sequencing batch reactor – SBR [10–13]. In these bioreactors, wastewater treatment processes occur sequentially in one tank and consist of several consecutive cycles, usually lasting from a few hours to several hours. The bioreactor operates cyclically, including several consecutive sequences: filling (phase I), reaction-mixing and aeration with mixing (phase II), sedimentation (phase III), decantation (phase IV) and possible dead phase (phase V). In order to provide the optimal conditions for the organisms carrying out biochemical processes, adequate homogenization of the bioreactor volume and oxygen quantity must be ensured during the aeration phase [14–16]. For the properly designed aerating systems, the oxygen concentration should reach a value of 2 mg O2/dm³ in a defined time interval (6–12 hours). Meeting this condition will ensure that the treatment process will run properly under the conditions of increased load of pollutants in wastewater. Good results are obtained by using alternating aeration, which allows the individual processes to take place under varying aerobic conditions [3,17–19]. The properly selected parameters of the aeration system in SBR bioreactors improve the structure of flocs, positively affecting their sedimentation capacity [3,8,18,20]. Therefore, the aeration phase is considered the most important stage of operation in SBR reactors [3,21].

Various types of aeration devices are used to ensure the adequate oxygen supply to microorganisms in activated sludge. Two basic groups of these devices can be distinguished: mechanical aeration devices and devices for aeration with compressed air [3,20,22]. The optimal solution is an aeration system characterized by high efficiency and low energy consumption while ensuring turbulence, which on the one hand causes full homogenization of the reactor, and on the other hand, does not tear or fragment the activated sludge flocs [3,8,23]. Aeration of the SBR bioreactor chamber can be realized using diaphragm disks or pipe diffusers which disperse compressed air delivered to the bottom of the chamber. They are also responsible for ensuring homogeneity of the system or even distribution of activated sludge flocs in the bioreactor volume.

The construction of prototypes of aeration devices and their experimental verification, especially at the initial stage, can be largely replaced by the use of computer simulations of computational fluid dynamics – CFD [17,24–26]. With the use of computer simulations, it is possible to obtain the knowledge of the mechanisms and hydraulic processes occurring in the bioreactor chamber in a short time, taking into account how the aeration systems work based on real data under different operating conditions [27,28]. CFD modeling also allows for quick elimination of incorrect design assumptions and enables analysis of the proposed solutions not only on a laboratory scale but also on a technical scale. From the economic point of view, the use of computer simulations should be encouraged, as it allows the design and initial testing of a new structure virtually – through numerical calculations, eliminating the need to build many prototypes of the modeled device [29–33].

In the paper, the results of model tests of the aeration and mixing process in a laboratory SBR reactor conducted using the ANSYS Fluent software were presented. The simulations were performed to verify the correct operation of the aeration device in the bioreactor. The data obtained from numerical calculations using the k-ε turbulence model were discussed. Owing to the results obtained during the numerical modeling, it is possible to predict which phenomena occurring in the bioreactor chamber affect the process of oxygenation and treatment of wastewater in a short period of time. The primary objective of this study was to compare the control concepts of the aeration process in terms of performance.
2. Materials and methods
The Euler-Euler model with Realizable $k$-$\varepsilon$ turbulence model was used to describe the hydrodynamic phenomena occurring in the two-phase system. This model satisfies the mathematical assumptions of Reynolds stresses and predicts the behavior of the fluid during flow through constrictions. In addition, it provides improved simulation results for flows that include rotation, rotation, boundary layer under strongly adverse pressure gradients, separation and recirculation, which ultimately enhance the performance of this model. This model introduces additional equations of turbulence kinetic energy balance (1) and turbulence energy dispersion rate (2), defined as $\varepsilon$ [2], respectively:

\[
k = \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho ku_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{1}
\]

\[
\varepsilon = \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial y_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon + \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon^2}} + C_1 \varepsilon \frac{C_3 \varepsilon}{k} G_b + S_\varepsilon \tag{2}
\]

The constants appearing in relation (1) and (2) take values determined empirically and usually are: turbulent Prandtl number for kinetic energy $\sigma_k = 1.0$, for energy dispersion $\sigma_\varepsilon = 1.2$, constants $C_{1e} = 1.44$; $C_2 = 1.9$; $C_1 = \max[0.43, \frac{\eta}{\eta + 5}]$. The parameter $\eta$ is determined according to relation (3).

\[
\eta = \frac{k}{\varepsilon} S \tag{3}
\]

The parameters $G_k$ and $G_b$ denote the turbulence kinetic energy generation due to averaging of velocity gradients and hydraulic displacement, respectively, and are described by relations (4) and (5).

\[
G_k = \mu_t S^2 \tag{4}
\]

\[
G_b = b g_i \frac{\mu_t}{\rho_i} \frac{\partial t}{\partial x_i} \tag{5}
\]

The parameter $Y_M$ reflects the contribution of turbulence dilation to the energy dissipation rate and determines the effect of fluid compressibility on turbulence in the flows with a large Mach number. The turbulent viscosity $\mu_t$, which in addition to $k$ and $\varepsilon$ completes the description of energy dissipation in a cascade of vortices, is defined by relation (6).

\[
\mu_t = \rho C_{\mu} \frac{\nu^2}{\varepsilon} \tag{6}
\]

The methods for determining the other parameters appearing in equations (1–9) are presented in the package documentation of the ANSYS Fluent Theory Guide [32].
The subject of the research involved diffusers in the shape of an inverted capital and small letter T made of acid-resistant pipe with a nominal diameter of 8 mm with 1 mm diameter holes arranged vertically downwards on the transverse profiles.

The diffusers were placed in vertical cylinders in the shape of a cylinder with internal diameter \( d_m = 80 \) mm and height \( h = 200 \) mm, filled with still water. The geometric model of the diffusers in cross-section with dimensions and the computational domain is shown in Figure 1. The computational domain was discretized by the finite element method consisting of 14060 elements and 14587 nodes for Model 1B (Figure 1B) and 58862 elements and 57103 nodes for Model 1D (Figure 1D).

![Figure 1. Models of aeration diffusers: (A,C) geometric model, (B,D) computational domain.](image_url)

The aeration simulation of the SBR tank chamber by the numerical method was carried out in ANSYS Fluent 2020 R1 software. Initial conditions were defined in FLUENT according to the characteristic physicochemical properties of air and liquid at a certain temperature, shown in Table 1. The reference pressure was set to atmospheric pressure.
Table 1. Physical and chemical properties of gases and liquids.

| Properties                      | Temperature [°C] |
|---------------------------------|------------------|
| Air density [kg/m³]             | 1.206            |
| Air viscosity [10⁻⁵ kg/(m·s)]    | 1.7722           |
| Water density [kg/m³]           | 999.7            |
| Water viscosity [kg/(m·s)]      | 0.001306         |
| Surface tension [N/m]           | 0.0742           |

The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) solver scheme was used for the solution of a steady-state with a Realizable k-ε turbulence model. A SIMPLE algorithm is a widely used numerical procedure in computational fluid dynamics (CFD) to solve the fundamental governing equations of fluid mechanics.

The momentum and turbulent kinetic energy were discretized using a first order upwind scheme, while the turbulence dissipation was discretized using a 2nd order upwind scheme, since it oscillates and does not converge when using a first order upwind scheme.

The time increment was taken as 0.001 s and 120 iterations per time step were performed in the simulation, which was sufficient to achieve convergence at each time step. Simulations were considered to converge when the scattering coefficient for mass, momentum, kinetic energy and dissipation rate fell below 1x10⁻⁴.

The boundary conditions were defined for aeration velocities of 0.01 m/s, 0.05 m/s, 0.1 m/s and 0.2 m/s. When running the simulations, attention was paid to the average velocity for the mixture and the intensity of turbulence.

3. Result and discussion

The aeration method of the SBR tank chamber was investigated by means of a numerical method in ANSYS Fluent 2020 R1 software. Tables 2 and 3 show the simulation results for aeration velocities of 0.01 m/s, 0.05 m/s, 0.1 m/s and 0.2 m/s and temperatures of 10°C and 20°C.

Table 2. Simulation results at 10 °C for Model 1B.

| Parameter              | Temperature [°C] | Speed [m/s] |
|------------------------|------------------|-------------|
|                        |                  | 0.01 | 0.05 | 0.10 | 0.20 |
| Average speed [m/s]    | 10               | 0.0010 | 0.0502 | 0.1009 | 0.2016 |
| Turbulence intensity [%]| 15.071           | 4.8039 | 6.3386 | 9.1432 |
| Average speed [m/s]    | 20               | 0.0100 | 0.0501 | 0.1014 | 0.2019 |
| Turbulence intensity [%]| 1.8167           | 4.1867 | 7.2181 | 9.1196 |

Table 3. Simulation results at 20 °C for Model 1D.

| Parameter              | Temperature [°C] | Speed [m/s] |
|------------------------|------------------|-------------|
|                        |                  | 0.01 | 0.05 | 0.10 | 0.20 |
| Average speed [m/s]    | 10               | 0.0006 | 0.0021 | 0.1009 | 0.2030 |
| Turbulence intensity [%]| 1.8167           | 4.1867 | 6.3805 | 9.2353 |
| Average speed [m/s]    | 20               | 0.0133 | 0.0535 | 0.1045 | 0.0238 |
| Turbulence intensity [%]| 1.793            | 4.8039 | 7.2698 | 9.2856 |
It was observed that for both models, the maximum values of the mean velocity increase proportionally to the aeration velocity (Figure 2). At other aeration velocities of 0.05 m/s and 0.1 m/s, the results are comparable. The values of average aeration velocity in the range of 0.01 to 0.2019 m/s obtained during modeling are comparable with the results obtained by Höhne and Mamedov [28]. From the graph in Figure 3, it can be concluded that Model 2 has the highest turbulence intensity at an aeration velocity of 0.2 m/s and a temperature of 20°C. The turbulence intensity during aeration ranged from 1.8 to 9.28%. These values are comparable to the averaged values of turbulence degree obtained by Liu et al. [29]. The distribution of kinetic energy in the considered diffusers is also similar, however, there are differences in the turbulence intensity in different areas of the reservoir. The zones with the highest ability to disperse solid particles and stagnant zones can be distinguished. This is due to the shape of the geometric model, as well as the velocity of air outlet through the holes, which determine the hydraulic process in the chamber. Simulations have shown that these are: the areas immediately adjacent to the diffuser outlet, the wall area near the bottom, and the central part of the circulation loop extending between the diffuser crossbars in Model 2 (Figure 4).

**Figure 2.** Average aeration velocities.

**Figure 3.** Turbulence intensity.
Figure 4. Turbulence intensity distribution for 0.2 m/s velocity: (A) Model 1 – 10°C, (B) Model 1 – 20°C, (C) Model 2 – 10°C, (D) Model 2 – 20°C.

4. Conclusion
This paper presents the results obtained from the simulations of the aeration process in a laboratory sequencing batch reactor (SBR) which were carried out for inlet velocities from 0.01 m/s to 0.2 m/s and temperatures of 10°C and 20°C, respectively. By analyzing the data in Figures 3 and 4, it can be seen that the maximum values of the average velocity and turbulence intensity for the mixture increase proportionally to the increase of the aeration value. These differences are caused by the shape of the geometric model and the velocity of the air exiting through the holes. These processes influence both the amount of oxygen dissolved in the bioreactor and the behavior of activated sludge flocs, starting from the degree of their dispersion in the chamber volume and ending with the possibility of disintegration under emerging stresses.
Simulations show that the aeration system presented in Figure 1D will ensure a higher intensity of turbulence in the chamber volume and will provide the required amount of oxygen in a given time.

References
[1] European Commission 1991 Council Directive of 21 May 1991 concerning urban waste water treatment (91/271/EEC) Off. J. Eur. Communities L 269 40–52
[2] Sid S, Volant A, Lesage G and Heran M 2017 Cost minimization in a full-scale conventional wastewater treatment plant: Associated costs of biological energy consumption versus sludge production Water Sci. Technol. 76 2473–81
[3] Drewnowski J, Remiszewska-Skwarek A, Duda S and Łagód G 2019 Aeration process in bioreactors as the main energy consumer in a wastewater treatment plant. Review of solutions and methods of process optimization Processes 7
[4] Zaborowska E, Czerwionka K and Makinia J 2017 Strategies for achieving energy neutrality in biological nutrient removal systems - A case study of the Slupsk WWTP (northern Poland) Water Sci. Technol. 75 727–40
[5] Zaborowska E, Majtacz J, Drewnowski J, Sobotka D, Al-Hazmi H, Kowal P and Makinia J 2018 Improving the energy balance in wastewater treatment plants by optimization of aerator control and application of new technologies Water Supply Wastewater Disposal; Politech. Lub. Lublin, Pol. 317–28
[6] Łaskawiec E, Fryczkowska B, Wyczarska-Kokot J and Dudziak M 2021 Physicochemical and ecotoxicological assessment of the fraction of impurities present in washings obtained in ultrafiltration and nanofiltration Desalin. Water Treat. 216 104–17
[7] Zhang X, Zhang F, Zhao Y and Li Z 2017 Start-Up and Aeration Strategies for a Completely Autotrophic Nitrogen Removal Process in an SBR Biomed Res. Int. 2017
[8] Łagód G, Piotrowicz A, Gleń P, Drewnowski J and Sabba F 2019 Modelling of sequencing batch reactor operating at various aeration modes MATEC Web Conf. 252 05013
[9] Zaburko J, Głowienka R, Widomski M K, Szulżyk-Cieplak J, Babko R and Łagód G 2020 Modeling of the aeration system of a sequencing batch reactor J. Ecol. Eng. 21 249–56
[10] Singh M and Srivastava R K 2011 Sequencing batch reactor technology for biological wastewater treatment: A review Asia-Pacific J. Chem. Eng. 6 3–13
[11] Babko R, Kuzmina T, Łagód G, Jaromin-Gleń K, Danko Y, Pawłowska M and Pawłowski A 2017 Short-term Influence of Drilling Fluid on Ciliates from Activated Sludge in Sequencing Batch Reactors J. Environ. Qual. 46 193–200
[12] Szaja A, Łagód G, Jaromin-Gleń K and Montusiewicz A 2018 The effect of bioaugmentation with Archaea on the oxygen uptake rate in a sequencing batch reactor Water 10 575
[13] Jaromin-Glen K, Babko R, Kuzmina T, Danko Y, Łagód G, Polakowski C, Szulżyk-Cieplak J and Bięganowski A 2020 Contribution of prokaryotes and eukaryotes to CO2 emissions in the wastewater treatment process PeerJ 2020 e9325
[14] Traoré A, Grieu S, Puig S, Corominas L., Thierry F, Polit M and Colprim J 2005 Fuzzy control of dissolved oxygen in a sequencing batch reactor pilot plant Chem. Eng. J. 111 13–9
[15] Sobotka D, Czerwionka K and Makinia J 2015 The effects of different aeration modes on ammonia removal from sludge digester liquors in the nitritation-anammox process Water Sci. Technol. 71 986–95
[16] Tang M and Liu J 2019 Aeration optimization of large-scale membrane bioreactors in a sewage treatment plant Water Pract. Technol. 14 198–202
[17] Habermacher J, Benetti A D, Derlon N and Morgenroth E 2015 The effect of different aeration conditions in activated sludge - Side-stream system on sludge production, sludge degradation rates, active biomass and extracellular polymeric substances Water Res. 85 46–56
[18] Zhang Y, Li C, Xu Y, Tang Q, Zheng Y, Liu H and Fernandez-Rodriguez E 2019 Study on propellers distribution and flow field in the oxidation ditch based on two-phase CFD model Water (Switzerland) 11
[19] Cui Y, Zhang H, Li X, Yang M and Guan Z 2018 Computational and experimental investigation of laminar flow mixing system in a pitched-blade turbine stirred tank *Int. J. Agric. Biol. Eng.* **11** 111–7

[20] Makowska M and Maciejewska E 2017 Effect of aeration time on the operation of SBR and SBBR reactor *Acta Sci. Pol. Form. Circumiectus* **15** 105–16

[21] Piotrowski R, Paul A and Lewandowski M 2019 Improving SBR performance alongside with cost reduction through optimizing biological processes and dissolved oxygen concentration trajectory *Appl. Sci.* **9** 2268

[22] Sivic A, Atanasova N, Puig S and Griessler Bulc T 2018 Ammonium removal in landfill leachate using SBR technology: Dispersed versus attached biomass *Water Sci. Technol.* **77** 27–38

[23] Leu S-Y, Rosso D, Larson L E and Stenstrom M K 2009 Real-Time Aeration Efficiency Monitoring in the Activated Sludge Process and Methods to Reduce Energy Consumption and Operating Costs *Water Environ. Res.* **81** 2471–81

[24] Ebrahimi M, Tamer M, Villegas R M, Chiappetta A and Ein-Mozaffari F 2019 Application of CFD to analyze the hydrodynamic behaviour of a bioreactor with a double impeller *Processes* **7** 694

[25] Tobo Y M, Bartacek J and Nopens I 2020 Linking CFD and kinetic models in anaerobic digestion using a compartmental model approach *Processes* **8** 703

[26] Siswantara A I, Daryus A, Darmawan S, Gunadi G G R and Camalia R 2016 CFD analysis of slurry flow in an anaerobic digester *Int. J. Technol.* **7** 197–203

[27] Rajavathsavai D, Khapre A and Munshi B 2014 Study of mixing behavior of cstr using cfd *Brazilian J. Chem. Eng.* **31** 119–29

[28] Shaheed R, Mohammadian A and Kheirkhah Gildeh H 2019 A comparison of standard k–ε and realizable k–ε turbulence models in curved and confluent channels *Environ. Fluid Mech.* **19** 543–68

[29] Höhne T and Mamedov T 2020 CFD simulation of aeration and mixing processes in a full-scale oxidation ditch *Energies* **13**

[30] Liu Y, Zhou L and Zhang Y 2019 Numerical simulation of bubble-liquid two-phase turbulent flows in shallow bioreactor *Energies* **12**

[31] Alizadeh M and Sadrameli S M 2018 Numerical modeling and optimization of thermal comfort in building: Central composite design and CFD simulation *Energy Build.* **164** 187–202

[32] ANSYS Inc 2013 Ansys Fluent Theory Guide *ANSYS Inc., USA* **15317** 724–46

[33] Kulisz M, Kujawska J, Przystupa B and Cel W 2021 Forecasting water quality index in groundwater using artificial neural network *Energy* **14**(18).