

Modelling of wastewater treatment plant operation under variable conditions

Modelowanie pracy oczyszczalni ścieków w zmiennych warunkach

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Modelling of the wastewater treatment plant in Żory, Poland was carried out using the BioWin 2.1 simulation program based on the real data regarding acquired in 2016-2017. It was made the static and dynamic calibration of the developed model of the treatment plant. The calibration and verification procedure was performed. In order to determine the optimal working conditions for the WWTP Żory, a series of simulation tests were carried out (44 simulations of the WWTP Żory model work). The simulations were carried out for: variable wastewater temperature, uniform and uneven distribution of wastewater to individual biological sequences, at variable sludge age and rate of the internal recirculation, and variable oxygen concentration in the nitrification and denitrification tanks. It was also investigated the influence of the external carbon source dosing, and the management method of wastewaters recycled from dewatering system, on the effectiveness of nitrogen removal in simulation conditions. The simulation studies resulted in determination of the optimal parameters for the WWTP Żory work, considering the variable inflow parameters, in order to intensify removal of the nitrogen compounds by biological means, and to achieve the target concentration of the total nitrogen at the outlet, i.e. 10 mgN/L.

Key words: modelling; activated sludge model; BioWin; computational simulation; wastewater treatment plant

Modelowanie oczyszczalni ścieków w Żorach prowadzono z wykorzystaniem programu symulacyjnego BioWin 2.1 w oparciu o dane rzeczywiste pozyskane w latach 2016-2017. Dokonano kalibracji statycznej i dynamicznej opracowanego modelu oczyszczalni. Przeprowadzono procedurę kalibracyjną i weryfikacyjną. W celu określenia optymalnych warunków pracy dla OS Żory wykonano szereg badań symulacyjnych (44 symulacje pracy modelowej OS Żory). Symulacje prowadzono dla: zmiennej temperatury ścieków, równomiernego i nierównomiernego rozdziału ścieków do poszczególnych ciągów biologicznych, przy zmiennym wieku osadu czynnego, stopniu recyrkulacji wewnętrznej i stężeniu tlenu w komorze tlenowej i denitryfikacji. Zbadano także wpływ dozowania zewnętrznego źródła węgla i sposobu gospodarowania wodami nadosadowymi na efektywność usuwania azotu w warunkach symulacyjnych. Efektem przeprowadzonych badań symulacyjnych było wyznaczenie optymalnych parametrów pracy OS Żory z uwzględnieniem zmiennych parametrów doptywu, w celu intensyfikacji usuwania związków azotu na drodze biologicznej i osiągnięcia docelowego stężenia azotu ogólnego na odpływie, tj. rzędu 10 mgN/L.

Słowa kluczowe: modelowanie, model osadu czynnego, BioWin, symulacja komputerowa, oczyszczalnia ścieków

Introduction

Biological treatment of wastewater on the basis of active sludge is a method commonly used in the treatment of municipal wastewater. Exploitation of a municipal wastewater treatment plant (WWTP) is a complicated task due to the need to control several technological processes at the same time, in such a way as to achieve the reduction of pollutants, required by law. There are different types of processes based on the active sludge method, including sequ-

ential biological reactors (SBR – *Sequencing Batch Reactor*), membrane bioreactors (MBR – *Membrane Bioreactor*) and conventional active sludge. Each of these processes uses a different configuration of the active sludge and the form of solid/liquid separation.

The complexity of wastewater treatment processes has increased significantly over the last decade due to the need to remove carbon, nitrogen and phosphorus compounds simultaneously. Currently, modelling and computer simulations are used to design a wastewater treatment sys-

tem and its control, as well as to predict the system behaviour. Mathematical modelling is an integral part of the design of the wastewater treatment system. The complicated nature of this system implies the need to support the design and operation with the use of computer programs. The application of mathematical models allows for analysis, which in a short time and at a low financial outlay enables to obtain many technological solutions, together with the simulation of events in the conditions typical for the real system [1-3].

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The most frequently used mathematical models for the design of biological wastewater treatment are the ASM active sludge models, such as ASM1, ASM2, ASM2d and ASM3. The models have been proposed by the International Water Association (IWA). The models with the active sludge or the ASM-based models are built into most of the currently used simulation programs, i.e. ASIM, BioWin, GPS-X, WEST, DESASS. When designing a model of a treatment plant, its calibration is important, i.e. adaptation to the set of information on the wastewater quality parameters at individual stages of treatment, in a full-scale treatment plant [4]. So far, several calibration methods have been developed [5-8], thanks to which it is possible to mimic the working conditions of the treatment plant in the existing state.

The simulation programs are increasingly used as a support tool in the field of design, commissioning or operation of the WWTP, and in particular for optimization of its operation conditions [9-14].

Objective of the work

The objective of the work was to support the decision making process in the field of optimizing the operation of wastewater treatment plant in Żory (WWTP Żory), by applying modelling of various scenarios of the mechanical and biological wastewater treatment plant in Żory, at variable operation parameters of treatment processes. The modelling of the WWTP was carried out using the BioWin 2.1 simulation program based on the real data collected in the years 2016-2017.

General characteristics of the object

The Wastewater Treatment Plant in Żory is located in the Silesian voivodeship. The WWTP Żory operates on the base on the classic 3-stage BARDENPHO system, referred to as the A2/O system. According to the assumptions of the process, the wastewater along with the active sludge flows sequentially through the chamber or

a separated anaerobic, anoxic and oxygen zone [15]. The designed equivalent number of inhabitants is 69791. The average daily flow (ADF) of raw wastewater to the treatment plant is 8128.0 m³/d. The quality of the treated wastewater does not exceed the assumed design parameters. Periodically, however, it was noted slightly exceeded concentration of the total nitrogen at the outflow, caused by low temperature of wastewater or irregularity of inflow. The simulation study aimed at developing various scenarios for the operation of the treatment plant in conditions of variable inflow parameters, in order to optimize its operation and adapt it to these conditions.

Modelling of the wastewater treatment plant operation

Modelling of the treatment plant operation was carried out using the BioWin 2.1 simulation program, distributed by the Canadian company Envirosim Associates Ltd. The developed model of the WWTP Żory treatment plant took into account the wastewater and sewage sludge line as well as the technological line of the wastewater from dewatering of digested sludge (Figure 1) and was configured based on the actual technical and technological data of devices and facilities of the WWTP Żory.

The model includes the load of pollutants, recycled with the wastewater from

dewatering process taking from the mechanical thickeners and filter presses to the beginning of the technological system, internal recirculation (IR) of nitrates to the pre-denitrification zones, excess sludge recirculation to the biological chambers, dosing of PAX as a precipitation agent for excess phosphates, daily unevenness of wastewater flowing into the individual lines of the WWTP Żory, and changes in the airing level of the transition chamber.

For configuration of the model the actual data were used, regarding flow, BOD₅, total suspended solids (TSS), alkalinity (pH), total nitrogen (TN) and total phosphorus (TP), obtained from the measurement campaigns carried out in the period of 24.08.2016–30.08.2016, 02.11.2016–08.11.2016, 22.03.2017–28.03.2017 (Table 1).

For calibration and verification of the model there were used results concerning quality of the treated wastewater discharged from the system in the period of 25.08.2016-31.08.2016, 03.11.2016-09.11.2016 and of 23.03.2017-29.03.2017, concerning the key indicators, i.e.: COD, BOD₅, TN, N-NH₄ and N-NO₃, general suspension (Table 1). In order to calibrate the model, the assessment of compliance of the results obtained during simulation tests with the real data was made for the following indicators: COD, BOD, TN, N-NH₄.

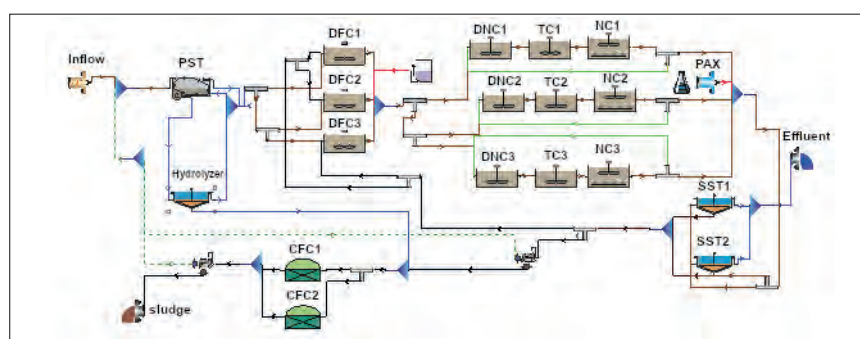


Fig. 1. The WWTP Żory model taking into account the biological part of the wastewater treatment plant developed in the BioWin simulator. Own study. PST – preliminary settling tank, DFC – dephosphatation chamber, DNC – denitrification chamber, TC – transitional chamber, NC – nitrification chamber, SST – secondary settling tank, DP – dewatering press, CFC – closed fermentation chamber

Table 1. The average weekly values of basic indicators of quality of the wastewater, inflowing and outflowing, from the period of 24.08.2016 – 29.03.2017, for configuration and simulation of the BioWin mod

Date	Flow	COD	TN	TP	N-NO ₃	pH	TSS	N-NH ₄	N-NO ₂	TOC	BOD ₅	Temp.
	m ³ /d	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	°C
INFLOWING WASTEWATER												
24.08.2016 – 30.08.2016	7 812	666	90,5	13,32	0,91	6,9	422	75,5	0,241	355	275	21
02.11.2016 – 08.11.2016	8 789	728	96,23	12,46	0,98	7,1	539	76,7	0,264	345	331	14
22.03.2017 – 28.03.2017	10 613	633	89,71	7,51	1,02	7,1	645	69,1	0,239	332	293	15
TREATED WASTEWATER												
25.08.2016 – 31.08.2016	7 298	40,9	13,46	1,40	10,93	7,4	12	0,024	0,051	19	5	17
03.11.2016 – 09.11.2016	8 473	34,9	18,50	0,77	13,53	7,5	8	1,69	0,312	55	6	13
23.03.2017 – 29.03.2017	10 030	54,8	21,3	0,88	6,23	7,5	23	9,69	0,997	21	7	13

Calibration of the model

As part of the simulation, a static and dynamic calibration of the model were carried out. The static calibration consisted of selection of the stoichiometric and kinetic constants. A part of the stoichiometric and kinetic constants values were adopted at the level proposed in the BioWin General Model. The proportions between the organic compound fractions expressed as COD, i.e. the molecular fraction and non-degradable fraction, and the easily decomposed fraction, have been experimentally determined. The calibration procedure was performed based on the results of the research from the measurement campaign, carried out in the period of 25-30.08.2016 (Table 1, until the model obtains conformity, in terms of the main indicators showing the efficiency of the treatment, i.e. TSS, COD, TN, N-NO₃, N-NH₄ and TP, with real values. Verification of the model was made for the data from the measurement campaign carried out in the period 03.11.2016 – 09.11.2016 (Table 1). The obtained values were in line with the average values of pollutant concentrations in the treated wastewater measured in this period. At this stage, the static calibration of the model has been completed. Subsequently, the model was calibrated dynamically, selecting the value of switching functions for autotrophic bacteria and heterotrophic bacteria by changing the maximum growth rate of autotrophs μ_A (from 0.5 to 0.9) and the oxygen concentration limit for the denitrification process (from 0.0 mg/L to 0.3-0.5 mg/L), in order to achieve very high convergence of the real results with the values obtained from the model.

Simulation tests

A series of simulation tests (44 simulations of the WWTP Żory model work) were performed, the task of which was to determine further directions of activities to optimize the operation of the WWTP Żory sewage treatment plant and to increase efficiency of the nitrogen removal, so as to achieve the total nitrogen concentration at the outlet in the range of 10 mg/L (target value) and 15 mg/L (limit value).

Results and their discussion

Model 0 – Simulation of the WWTP Żory work in different seasons (summertime, wintertime)

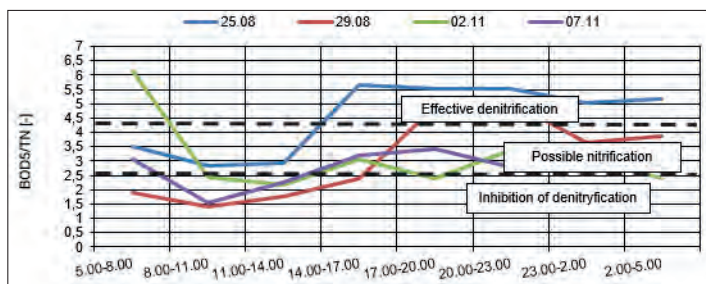
The simulation tests were carried out at variable temperature of incoming waste-

water, i.e. 22°C (summertime) and 8°C (wintertime). The results of the analyses are summarized in Figure 2.

The effective denitrification occurs when the organic compounds in the amo-

lative denitrification is possible. However, in the wintertime there is a shortage of easily decomposable organic compounds, what may result in inhibition of the denitrification process ($BOD_5/TN < 2.5$) (Figure 2).

Fig. 2. Change in ratio BOD_5/TN in the wastewater incoming to the WWTP Żory in the summertime and wintertime



unt of 7 times higher than the load of nitrogen compounds are supplied into the biological system. It has been observed that in the wintertime there is a significant shortage of organic compounds flowing into the WWTP, and the COD/TN ratio value amounts to 4–6. Stable conditions for the denitrification process are obtained when the COD/TN ratio value is higher than 5.88 (in the summertime) and 6.13 (in the wintertime) [16]. In the case of wastewater flowing into the WWTP Żory their quality in the summertime meets the above requirements because the COD/TN ratio value exceeds 7. However, in the wintertime it is advisable to dispense an external source of organic carbon. For effective denitrification, it is also important what part of organic contaminants make the readily biodegradable organic compounds (expressed by the BOD₅ indicator). The analysis showed that in the summertime, in the morning and in the afternoon, the amount of readily biodegradable organic compounds is insufficient, what may contribute to the inhibition of the denitrification process. However, in the evening the BOD₅/TN ratio exceeds the value 2.5, and even is above 4.5, therefore the effec-

Model 1 – Simulations of the influence of change in the wastewater distribution

Due to uneven operation of the biological chambers of the WWTP Żory, resulting mainly from the lack of zoning by separation of the wastewater into the three technological lines (L1, L2, L3), the simulations were carried out at the change of the wastewater distribution method. In the first period of the study, the simulations were carried out at the even wastewater distribution to the biological sequences (i.e. 33% · ADF was flowing into each of the technological lines). In the second period of the simulation study, the wastewater distribution was uneven, i.e. to L1 = 50% · ADF, to L2 = 30% · ADF, and to L3 = 20% · ADF.

The results of modelling showed that the uneven distribution of wastewater influences variation of the active sludge age (Solid Retention Time, SRT), which periodically increased up to 21 days and rapidly dropped to the value of 9 days (Figure 3).

Fluctuations in the sludge age at uneven wastewater inflow lead to breakdown of the nitrification process and cause an increase in amount of nitrogen (total and ammonium) in the outflow (Figure 4). The

Fig. 3. The influence of a method of the wastewater distribution to the technological lines on the stability of the active sludge age in the biological reactors

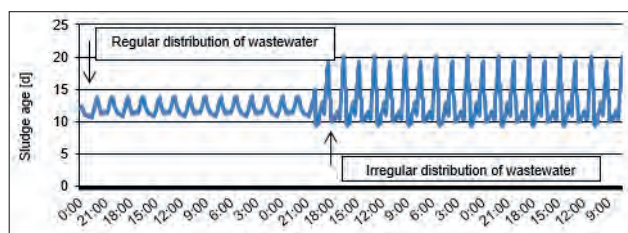
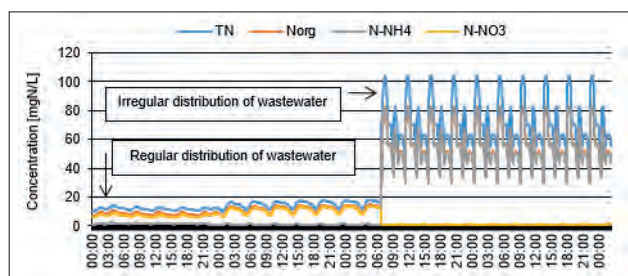


Fig. 4. The influence of a method of the wastewater distribution to the technological lines on concentration of the nitrogen compounds in the outflow



amount of ammonium nitrogen in the outflow equalled even to 43.0 mg/L.

Model 2 – Simulations of the influence of change in the temperature and the sludge age

Simulation studies were carried out, which aim was to select the optimal age of sludge for a given season. The results obtained in the BioWin model have shown that in the existing wastewater treatment system, the extension of the sludge age over 18 days in the summertime results in an increase in concentration of the ammonium nitrogen and nitrates in the outflow from the reactor. Keeping the sludge age at the level of 20 days causes that the amount of total nitrogen in the outflow exceeds the limit value of 15 mgN/L. The excessive sludge age prolongation decreases the denitrification efficiency. The reduction in the denitrification efficiency is caused by the long sludge holding in the secondary settling tank, which results in the process of secondary denitrification. Then, higher concentrations of basic indicators of impurities in the outflow are observed. The optimal sludge age for this season is 10-15 days (Figure 5).

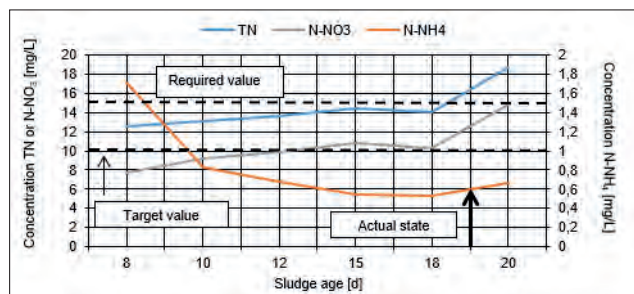
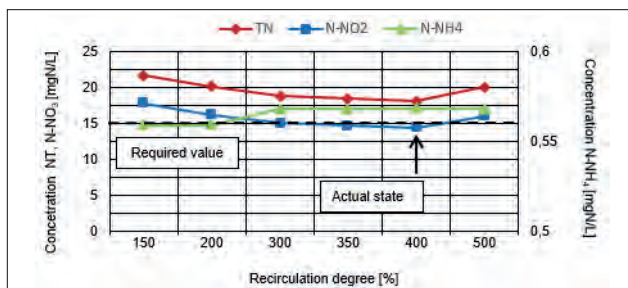
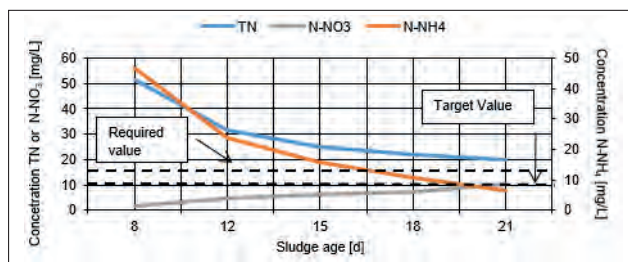


Fig. 7. Influence of the active sludge age on concentration of the nitrogen compounds in the treated wastewater in the wintertime

Fig. 8. Influence of the internal recirculation rate on concentration of the nitrogen compounds in the treated wastewater – parameters of the system: SRT = 20 d, temperature of wastewater = 22°C



showed that when the sludge age drops below 10 days, the nitrification and denitrification process completely breaks down. Extending of the sludge age increases efficiency of the nitrogen removal from the wastewater. The simulation studies have shown that the extension of the sludge age in the wintertime affects efficiency of the nitrogen removal, however concentration of

lowering the nitrate concentration and thus the total nitrogen in the outflow. The efficiency of nitrogen removal increases by approx. 4.3% (Figure 8). Increasing degree of the recirculation above 400% results in a decrease in the efficiency of denitrification, which is most probably related to the recirculation of excessive amounts of the oxygen to this zone, together with nitrates. As a result, the concentration of nitrates in the treated wastewater increases by approx. 12%.

Similar relationships were observed when the system worked at the optimum sludge age for a setpoint wastewater temperature. Shortening the sludge age of the active sludge caused an increase in efficiency of removing of the nitrogen compounds by about 27%. This value was calculated on the base of the difference between concentration of the total nitrogen at the outlet in the system of SRT = 20 d and the system of SRT = 12 d for IR = 300%. Increasing rate of the internal wastewater recirculation from 300% · ADF to 400% · ADF caused the increase in efficiency of removing of the total nitrogen by about 1.25%. On the other hand, increasing rate of the internal recirculation above 450% · ADF caused the increase in outflow of the nitrogen in nitrates by about 2% (Figure 9).

Model 4 – Simulation of wastewater treatment process with variable capacity of denitrification zone

The simulation studies were carried out with a variable ration between the denitrification zone volume and total reactor volume (VD/VR), in the range of 0.25-0.5 by changing of oxygen concentration in the transitional chamber, in the range of 0-1 mg/L. The results of the simulation showed that conducting the treatment process with the reduced volume of the anoxic zone

The studies carried out with the help of the BioWin program have shown that in the transitional seasons, i.e. in the spring and autumn, the minimum age of sediment is 10 days, and the recommended age up to 20 days. Extending the sludge age above 10 days results in doubling of the nitrate intake rate and improves denitrification efficiency (Figure 6).

In the wintertime, when the temperature of wastewater drops to 8°C, the efficiency of removing nitrogen compounds decreases (Figure 7). Analysis of the modelling results

the total nitrogen at the outflow is above 10 mg/L. In order to achieve higher efficiency of the wastewater treatment it is necessary to take further optimization measures.

Model 3 – Simulation of the influence of change of internal recirculation coefficient

Simulation tests were carried out changing the rate of the internal recirculation in the range of 150–550% · ADF. Increasing rate of the internal recirculation from 300% to 400% · ADF causes growing of the efficiency of denitrification, which results in

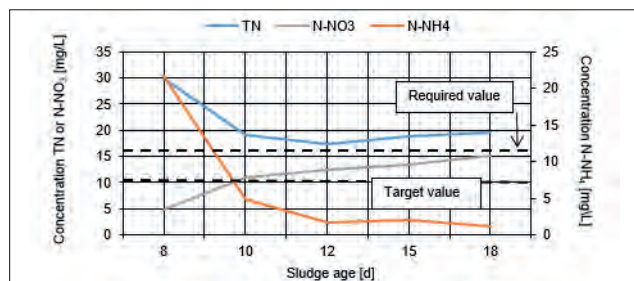


Fig. 6. Influence of the active sludge age on concentration of the nitrogen compounds in the wastewater treated during the transitional period

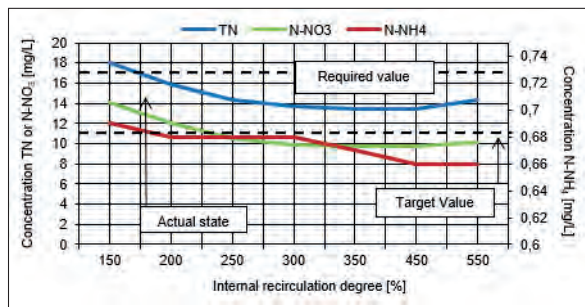


Fig. 9. Influence of the internal recirculation rate on efficiency of the nitrogen removal – parameters of the system: SRT = 12 d, temperature of wastewater = 22°C

(VD/VR < 0.5) results in a complete breakdown of the process of removing the nitrogen compounds from the wastewater. The amount of total nitrogen at the outlet in this case was approx. 50 mg/L (Figure 10).

The results of simulation tests showed that denitrification is possible only when the VD/VR ratio is 50% (concentration of oxygen in the transition chamber – 0 mg/L) (Figure 10). The results obtained as part of the computer simulation also showed that reducing volume of the anoxic zone affects the process of reduction of nitrates to gaseous nitrogen. It was found that in a system where VD/VR ratio is 0.5 oxygen intake is used primarily for processes related to the metabolism of nitrifying and denitrifying bacteria. Less oxygen is taken up by micro-

pre-denitrification. This solution allows the use of organic compounds contained in the wastewater as a source of carbon for the respiration processes for the denitrifying microorganisms. The efficiency of pre-denitrification is limited. The literature sources report that the maximum efficiency of remo-

val of the nitrates in the denitrification zone in systems with pre-denitrification is up to 80% [16]. These limitations result from the discussed above maximum rate of recirculation of the nitrates from the oxygen zone to the anoxic zone, the volume of this zone, the quality and quantity of the organic compounds in the wastewater flowing into this zone. In order to support the denitrification processes in these systems, it is possible to maintain such oxygen concentration in the oxygen chambers that the simultaneous denitrification in this zone was ensured. The results of simulation tests for introducing the simultaneous denitrification process in the aerobic zone by lowering the concentration of oxygen in this zone from 2 mg/L to 0.6 mg/L are presented below.

Fig. 12. The value of the oxygen uptake rate for oxidation of the organic compounds and nitrogen contained in wastewater at the ratio VD/VR = 0.25

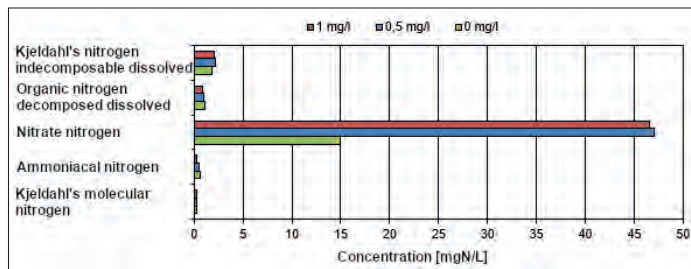
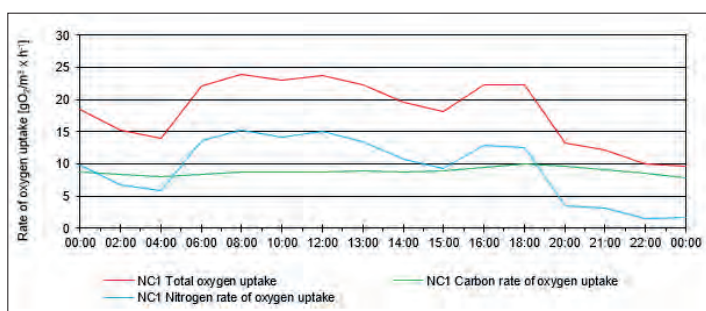


Fig. 10. Influence of concentration of oxygen in the transitive chamber on content of the individual nitrogen forms in the wastewater after treatment

Model 5 – Simulations of change of the oxygen concentration in the aerobic zone

The simulation studies have shown that lowering the oxygen concentration in the oxygen chambers from 2 mgO₂/L to approx. 0.8 mgO₂/L decreases the concentration of total nitrogen in the outflow by approx. 2% (Figure 13). This is caused

organisms for carbon oxidation processes. A change in the VD/VR ratio to 0.25 has resulted in less oxygen being used by the denitrifying bacteria. However, the oxygen uptake ratio (OUR) for carbon oxidation has increased, especially between 19 pm and 4 am (Figure 11 and 12).

In the WWTP Żory treatment plant it is used the wastewater treatment process with

Fig. 13. Influence of oxygen concentration in the oxygen chamber on the concentration of nitrogen compounds in the treated wastewater (SRT = 12 d, T = 22°C)

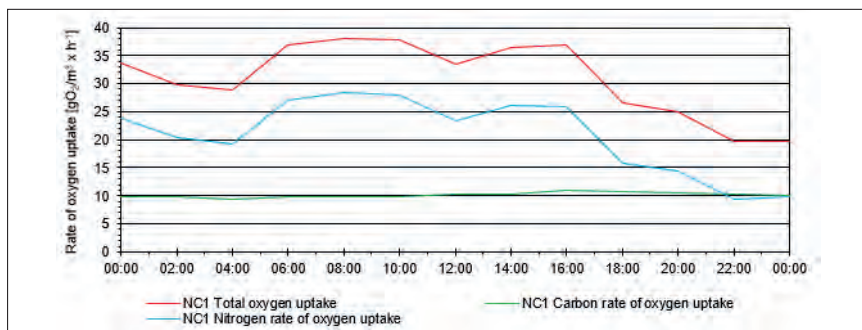
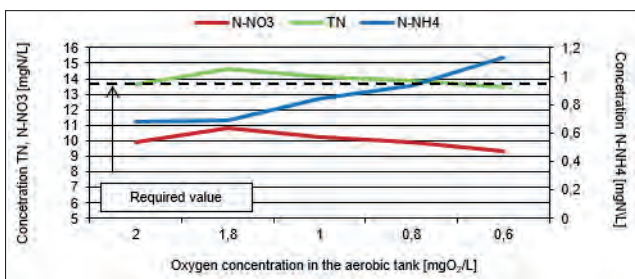


Fig. 11. The value of the oxygen uptake rate for oxidation of the organic compounds and nitrogen contained in wastewater at the ratio VD/VR = 0.5

by the decrease in concentration of nitrates in the treated wastewater. However, it should be noted that with the decrease of oxygen concentration in the nitrification chamber, the concentration of ammonium nitrogen in the outflow increases, because the living conditions for nitrifying microorganisms are deteriorating, the optimum of which is at the oxygen concentration of approx. 2 mg/L. The introduction of such a change in the system could seriously disrupt the operation of the treatment plant during a period of low tempe-

ratures, when the efficiency of nitrification decreases.

Model 6 – Simulation of dosing of the external source of organic carbon

The studies simulating dosing of the external carbon source (ECS) to the reactor chambers were carried out so that the COD/TN ratio was 8, and the ratio BOD5/TN was 5. Compared to the results in taken in the summertime and presented in Figure 12, it can be seen that the efficiency of total nitrogen removal increased after dosing an external carbon source. The concentration of total nitrogen in the treated wastewater was observed not higher than 12 mg/L (Figure 14). However, in the simulations where no

Model 7 – Simulation of change in the management of wastewater recycled from dewatering system

The wastewater from dewatering system returned to the wastewater treatment system contain a hardly decomposable fraction of

the total nitrogen at the outlet did not exceed the limit value ($c_{av.TN} = 14.8$ mg/L, $c_{av.N-NO3} = 10.6$ mg/L, $c_{av.N-NH4} = 1.06$ mg/L) (Figure 17).

In the same system (without returning wastewater from the dewatering sewage)

Fig. 17. Simulation tests of the WWTP Żory operation with a limited inflow of leachates to the biological zone (SRT = 20 d, T = 22 °C)

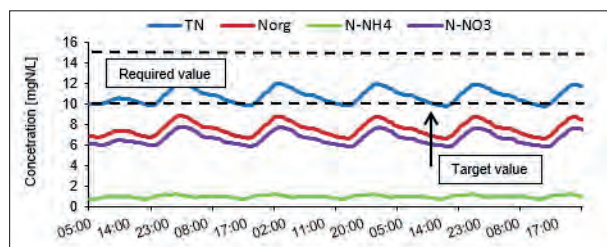
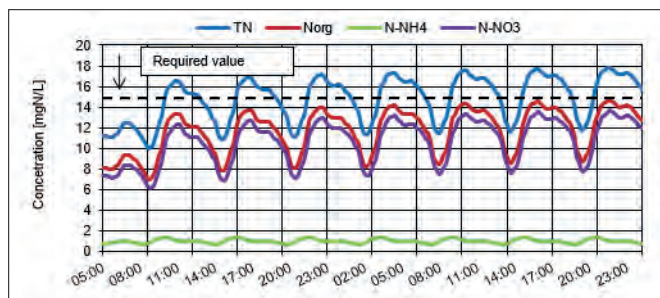


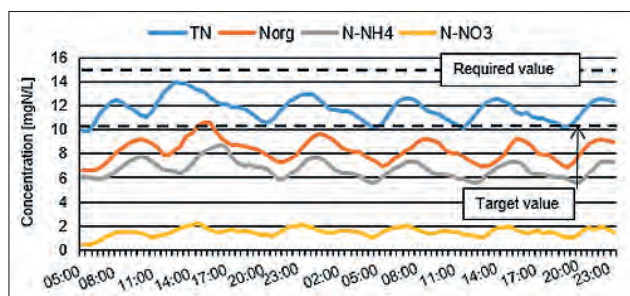
Fig. 14. The concentration of nitrogen compounds in the treated wastewater in the summertime (SRT = 12 d, T = 22 °C) after dosing of external carbon source

the external carbon source dosing was simulated. Simulation tests showed that the content of total nitrogen, even during the periods of inflow of the increased pollutant load, did not exceed the permissible value, i.e. 15 mgTN/L at the outflow from the treatment plant (Figure 18).

external carbon source was dosed, the total nitrogen content at the outflow was about 14 mg/L in the summertime (Figure 12). In addition, the results of simulations carried out in transitional period (T=15°C) showed that the nitrogen removal efficiency after dosing an external carbon source is still high and below 14 mg/L (Figure 15).

In the wintertime, despite dosing of ECS, the total nitrogen content in treated wastewater varied between 15.0 mgN/L and 18.5 mgN/L, which results from the inhibition of nitrifying bacteria activity at these temperatures and the increase in concentration of the ammonium nitrogen at the outflow (Figure 16).

Fig. 18. Simulation tests of the WWTP Żory operation with a limited inflow of leachate to the biological zone and at dosing of ECS (SRT = 20 d, T = 22 °C)



the wastewater, which adversely affects the functioning of the whole treatment plant.

The simulation studies have shown that the wastewater treatment plant works more efficiently at without the inflow of the dewatering sewage, and the average content of

SUMMARY

As a result of the simulation tests, the optimal parameters of the WWTP Żory work were determined in the summertime, transitional periods and the wintertime. Optimization of operation of the treatment plant serves to improve the wastewater treatment, especially in scope of removing nitrogen compounds so that the concentration of total nitrogen at the outlet does not exceed 15 mgN/L, and even maintained below 12.0 mg/L. Table 2 summarizes results of simulation for 7 treatment plant models. Based on the obtained results, it was found that the highest efficiency of removing nitrogen compounds from the wastewater (concentration of total nitrogen at the outlet below 12.0 mg/L) can be obtained thanks to the dosing of the external source of carbon and proper management of the supernatant water. Dosing of the external source of the organic carbon (ECS) at the temperature of 22°C and 15°C, and SRT = 12d, 15d and 18d, allows to obtain concentration of TN at the outlet in the

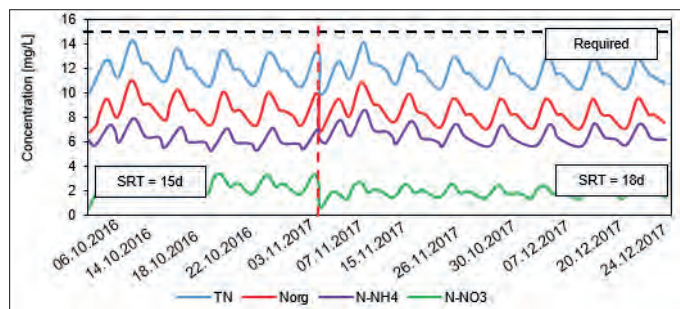


Fig. 15. The concentration of nitrogen compounds in the treated wastewater in the transitive period (SRT = 15 d, 18 d, T = 15 °C) after dosing of external carbon source

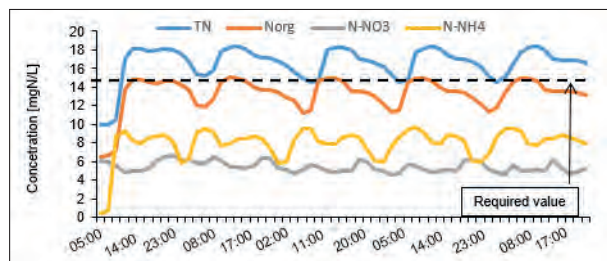


Fig. 16. Influence of dosing of ECS on the concentration of nitrogen compounds in the treated wastewater in the wintertime (SRT = 20 d, T = 8 °C)

Table 2. Summary of results of simulations carried out using the models 1–8

Model name	Variable technological parameter	Concentration of total nitrogen in the outflow	
		TN ≤ 15 mg/L	TN < 12 mg/L
Model 1 – Simulation of the influence of change in the wastewater distribution	W1: Regular distribution of wastewater L1: 33% x ADF L2: 33% x ADF L3: 33% x ADF	YES	NO
	W2: Irregular distribution of wastewater L1: 50% x ADF L2: 30% x ADF L3: 20% x ADF	NO	NO
Model 2 – Simulation of the influence of change in the temperature and the sludge age	W1: T = 22°C SRT = 8d, 12d, 15d, 18d, 20d	YES For SRT = 8–18d	NO
	W2: T = 15°C SRT = 8d, 12d, 15d, 18d, 20d	NO	NO
	W3: T = 8°C SRT = 8d, 12d, 15d, 18d, 20d	NO	NO
Model 3 – Simulation of the influence of change of internal recirculation coefficient	W1: T = 22°C, SRT = 20d IR = 150%, 200%, 300%, 350%, 400%, 500%	NO	NO
	W2: T = 22°C, SRT = 12d IR = 150%, 200%, 300%, 450%, 550%	YES For I_{RZ} = 225–550%	NO
Model 4 – Simulation of the wastewater treatment process with variable capacity of denitrification zone	W1: SRT = 20d, T = 15°C VD/VR = 0,5	YES	NO
	W2: SRT = 20d, T = 15°C VD/VR < 0,5	NO	NO
	W3: SRT = 20d, T = 15°C VD/VR = 0,25	NO	NO
Model 5 – Simulation of change of the oxygen concentration in the aerobic zone	W1: T = 22°C, SRT = 12d c_{O_2} (AC) = 0,6 mg/L, 0,8 mg/L, 1 mg/L, 1,8 mg/L, 2,0 mg/L	YES For c_{O_2} (KN) = 0,6–2,0 mg/L	NO
Model 6 – Simulation of dosing of the external source of organic carbon	W1: T = 22°C, SRT = 12d	YES	YES Concentration of TN in the outflow in the range of 9,8–12,0 mg/L
	W2: T = 15°C, SRT = 15d, 18d	YES	YES/NO Concentration of TN in the outflow in the range of 10,5–13,5 mg/L
	W3: T = 8°C, SRT = 20d	NO	NO
Model 7 – Simulation of change in the management of wastewater recycled from dewatering system	W1: T = 22°C, SRT = 20d No recycle of supernatants to the biological chambers	YES/NO Concentration of TN in the outflow in the range of 11,0–17,0 mg/L	NO
	W2: T = 22°C, SRT = 20d No recycle of supernatants to the biological chambers + dosing of ECS	YES	YES/NO Concentration of TN in the outflow in the range of 10,5–13,0 mg/L

range from 9.8 mg/L to 13.5 mg/L. Limitation of inflow of the supernatant water with simultaneous dosing of the ECS allows to obtain concentration of TN at the outlet in the range from 10.5 mg/L to 13.0 mg/L. Lack of the ECS dosing to the biologic chambers results in higher concentrations of total nitrogen at the outlet, with the total nitrogen concentration not exceeding the limit value 15.0 mg/L. The improvement of efficiency of the wastewater treatment can also be achieved by controlling the rate of oxygen of the wastewater in the nitrification and denitrification chamber, as well as by the uniformed distribution of the wastewater to the individual process sequences. Concentration of the total nitrogen in the wastewater after treatment, in these cases, is below 15,0 mg/L.

The optimal conditions for the process of wastewater treatment were determined:

- 1) Uniformed wastewater distribution (33% x ADF for each technological sequence),
- 2) Temperature of the wastewater and the sludge age, T = 22°C and SRT = 8–18 d, respectively

- 3) Rate of the internal recirculation for T = 22°C and SRT = 12 d equal to IR = 225–550%,
- 4) Concentration of oxygen dissolved in the transitive chamber $c_{O_2} = 0$ mg/L for T = 15°C and SRT = 20 d,
- 5) Concentration of oxygen dissolved in the oxygen chamber $c_{O_2} = 0.6–2.0$ mg/L for T = 22°C and SRT = 12 d,
- 6) Dosing of the external source of organic carbon to the wastewater of temperature T = 22°C and SRT = 12–20 d.

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