Use of computer simulation for cycle length adjustment in sequencing batch reactor

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Abstract The city of Nowy Targ located in Poland's highland operates the WWTP with classic SBR technology. In winter some decrease in process efficiency was observed. The research described in the paper was aimed at using computer simulation to adjust SBR cycle length and structure in order to minimize the effects of low wastewater temperature on biological CNP removal. The simulations performed at 6°C wastewater temperature showed that switching from 6 to 8 hours cycle and extension of the aeration phase length from 2.75 to 5 hours will increase the effectiveness of biological nitrification and biological phosphorus removal. The change in practice will not affect COD value in the effluent. Based on the simulation results a new SBR operational strategy was proposed for Nowy Targ WWTP.

Keywords Activated sludge; computer simulation; nutrient removal; sequencing batch reactor; wastewater

Introduction

The wastewater treatment plant in Nowy Targ in southern Poland with design capacity of 21,000 m^3/d (at present 12,000 m^3/d) uses the technology of sequencing batch reactors (SBR) for biological wastewater treatment. Technological layout of the plant is shown in Figure 1. The plant, being one of the largest in Europe applying classic SBR technology, encounters decreased nitrogen removal efficiency during low wastewater temperature periods. Figure 2 shows the relation between concentration of ammonia nitrogen in effluent and influent wastewater temperature. Full nitrification with NH_4–N concentrations close to 0 g/m^3 was achieved during the period from May to November, when temperature was above 10°C.

The problem was to adjust the SBR cycle length and structure in such a way that full nitrification was obtained during low temperature periods without lowering effectiveness of biological denitrification and enhanced phosphorus removal. Computer simulation was used to achieve this goal. Simulations were carried on with program SimWorks™ using predefined

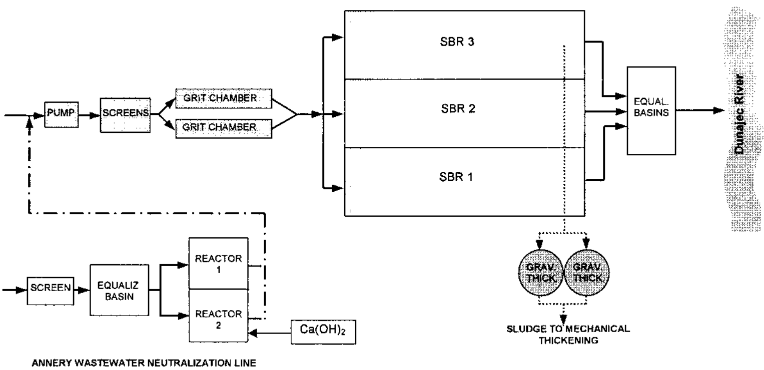

Figure 1 Layout of the Nowy Targ WWTP

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Table 1 Average concentrations of pollutants in influent and effluent during the sampling program

Indicator	15.09.97		25.09.97		27.10.97	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
COD, gO_2/m^3	671	56	1040	64.3	1085	66.6
BOD_5, gO_2/m^3	239	7.6	334	24.6	-	-
Suspended solids, g/m^3	239	5.60	407	32.2	394	-
NO_x–N, gNO_x–N/m^3	1.8	10.6	0.1	2.7	0.2	3.4
NH_4–N, gNH_4–N/m^3	23.6	0.5	27	3.0	31.6	2.7
TKN, gN/m^3	45.4	3.1	54.2	5.1	54.3	3.8
TP, gP/m^3	3.6	0.08	4.0	0.33	9.3	0.13

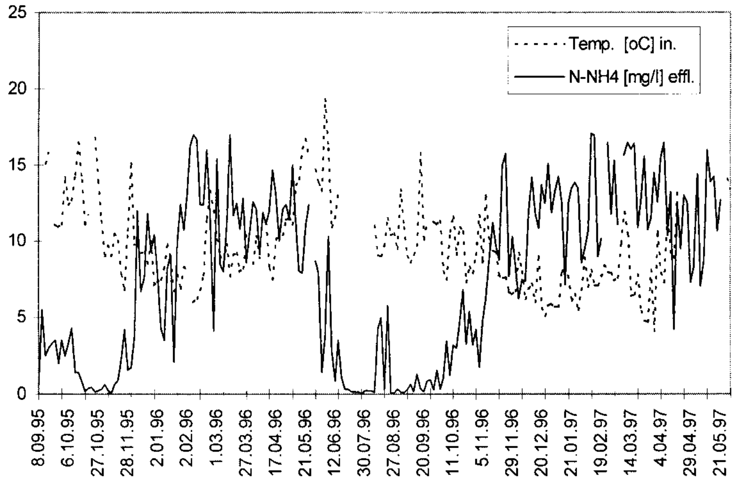

Figure 2 Effluent ammonium concentration as a function of the influent temperature

layout of a SBR plant. The model allows for simulation of biological degradation of organic material, nitrification, denitrification and enhanced phosphorus removal in a cyclic SBR reactor. A specific feature of SBR reactors at Nowy Targ WWTP is their elongated shape and designated anoxic zone at the end of each reactor. This is a significant deviation from the assumption about complete mixing usually made when modelling cyclic reactors.

Methods

Sampling program

The research was based on analytical data on wastewater composition and sludge properties gathered at Nowy Targ WWTP in September and October 1997 during the joint research program carried out by Cracow University of Technology (CUT) and Royal Institute of Technology in Stockholm (Banas *et al.*, 1999; Styka *et al.*, 1998; Sharif, 1998). The analytical sampling program was performed on the following days:

- *15.09.1997* – samples taken in influent to the plant (12 samples during 24 hours, each was 2-hour composite sample) and in effluent from equalization tank (single 24-hour composite sample).
- *25.09.1997* – samples taken in influent to SBR nr 2 (single 2-hour composite sample with 1 minute intervals during filling phase) and in effluent from SBR nr 2 (1 sample of 10 l volume taken during decantation phase).

Table 2 Values of kinetic constants after calibration of the model of SBR nr 2 at Nowy Targ WWTP

No.	Kinetic constants	Symbol	Unit	Default value	Steady-state calibration	Dynamic calibration
1	Max growth rate for autotrophs	μA	1/d	0.75	0.7	0.6
2	Decay rate for autotrophs	b_A	1/d	0.04	0.02	0.02
3	Ammonia half-saturation constant	K_{NH}	g/m^3	1.0	0.85	1.2
4	Max growth rate for heterotrophs	μ_H	1/d	3.2	2.5	2.5
5	Decay rate for heterotrophs	b_H	1/d	0.62	0.3	0.3
6	Substrate half-saturation constant	K_S	g/m^3	5	10	15
7	Max growth rate for poly-P heterotrophs	μ_{PH}	1/d	0.9/0.42	4/0.2	4/0.2
8	Decay rate for poly-P heterotrophs	b_{PH}	1/d	0.04	0.01	0.01

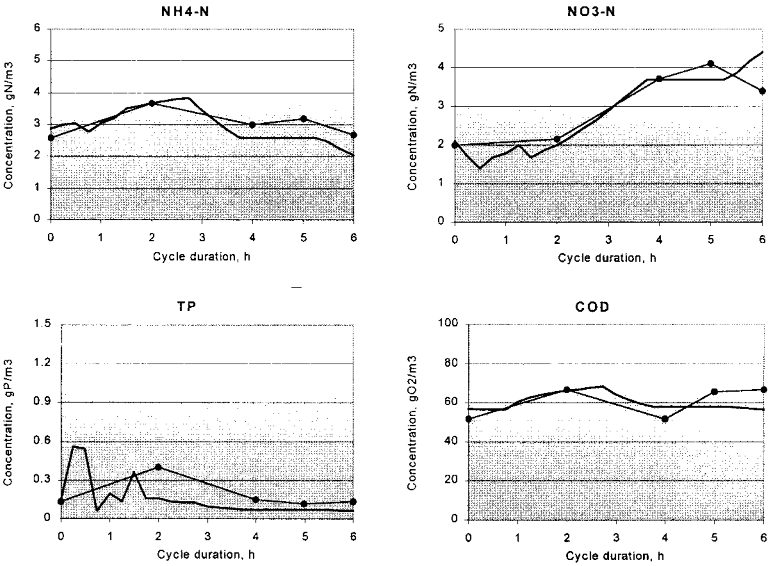

Figure 3 Results of dynamic calibration of the model of SBR nr 2 at Nowy Targ WWTP
(●: observations; —: simulation)

- *27.10.1997* – incidental samples taken after each phase during one cycle of the SBR nr 2 at three points: at the influent, in the middle of the reactor's length, and at the end of the reactor.

All analytical analyses were preformed by the Nowy Targ WWTP laboratory's personnel with use of routine methods and instruments and at the CUT laboratory. All analyses were performed according to the Polish standards. Analyses of VFA were done using gas chromatography. Average pollutant concentrations in influent and effluent during the sampling program are presented in Table 1.

Model calibration

Steady-state calibration of the model was done with the use of data about composition of wastewater entering the SBR nr 2 during filling period and discharged during decanting phase on 25.09.97. Values of the model's kinetic parameters were gradually changed to minimize the sum of squared relative deviations of the effluent concentrations obtained from simulations and those from observations. The pollutants of interest were: COD, NH_4–N, NO_x–N, and TP. At the end of steady-state calibration the values of relative deviations were as follow: 1% for COD; 2% for NH_4–N; 8% for NO_x–N; and 20% for TP. It should be noted that high value of relative deviation for TP could be associated with low concentration of phosphorus in effluent (about 0.3 mgP/l).

The values of kinetic constants obtained from steady-state calibration became a starting point for dynamic calibration of the model. During dynamic calibration simulated concentrations in effluent were compared to the results of wastewater analyses performed during a single cycle of the SBR nr 2 on 27.10.97. The final results of dynamic calibration of the model are shown in Figure 3. In Table 2 the values of kinetic constants: default in the model, after steady-state calibration and after dynamic calibration are presented.

New operational strategy

Defining the strategy

During the research the SBRs at Nowy Targ WWTP were operated in 6-hour cycles subdivided into the following phases:

- filling and mixing - 1.25 h
- filling and aeration - 0.75 h
- aeration - 2 h
- sedimentation - 1 h
- decanting - 1 h

When operating the SBR in a 6 hour cycle with relatively short aeration phase the process efficiency strongly depends on temperature. This is especially true for biological nitrification. In winter nitrogen concentration in effluent is much higher than in summer (e.g. at Nowy Targ WWTP average TN in winter 1998 was 20 gN/m^3 while annual average was 15 gN/m^3). Results of the research of Oleszkiewicz and Berquist from 1988 confirm these observations. As a method for enhancing process efficiency they propose decreasing the sludge F/M ratio, raising sludge age and extending the time of the cycle. The latter is associated with reducing hydraulic capacity of the plant.

The strategy proposed for Nowy Targ WWTP was to extend the cycle time from 6 to 8 hours in the periods when wastewater temperature is low. Special attention was paid to duration of the aerobic phase during filling and reaction which is the most important factor for biological nutrient removal in SBR. During further research efforts were focused at finding the optimum aeration phase length under low temperature conditions and forecasting the technological results.

Finding optimum length of aeration phase

It has been assumed that when operating the SBRs in Nowy Targ WWTP under an 8-hour cycle the length of the following phases will be kept constant:

- total length of filling phase T_N - 2.66 h
- length of sedimentation phase T_S - 1.0 h
- length of decanting phase T_D - 1.0 h

Consequently, only duration of the aeration phase T_{O2} can be changed during the cycle. Aeration phase usually includes a part of filling phase (T_{N+O2}) and entire reaction phase (T_R). According to the Eq. (1) the length of the aeration phase T_{O2} can be set at any value from 0 to 6 hours.

$$T_{N+M} + T_{N+O2} + T_R + T_S + T_D = 8 \qquad (1)$$

where:

T_{N+M} – duration of the filling and mixing phase

$T_N = T_{N+M} + T_{N+O2}$ – total duration of the filling phase

$T_{O2} = T_{N+O2} + T_R$ – total duration of the aeration phase

Table 3 Equations of the approximation functions obtained from sensitivity analysis

Approximation function equation	Multiple correlation coefficient *R*	F value	p value
$V_{NH4} = 4.56 + 0.36*TEMP + 0.70*TKN$	0.787	10.59	< 0.00187
$V_{NO3} = 3.25 + 0.83*ChZT + 0.40*TKN$	0.924	38.16	< 0.00000
$V_P = 0.36 + 0.54*T_{O2}$	0.540	5.762	< 0.03084
$V_{ChZT} = 79.2 + 0.99*ChZT$	0.990	719.4	< 0.00000

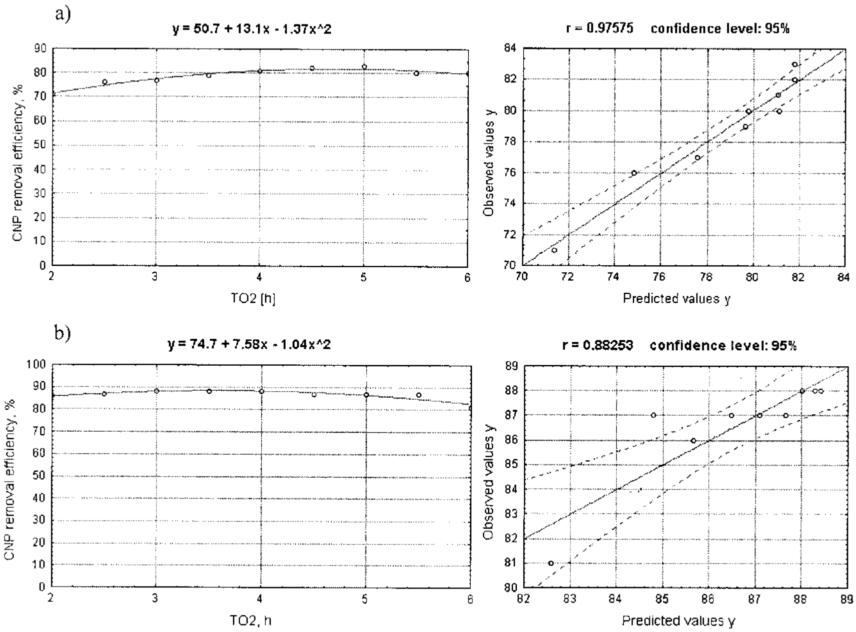

Figure 4 Simulated relationship of CNP removal efficiency and duration of the aeration phase in SBR in Nowy Targ at wastewater temperature 6°C (a) and 14°C (b)

The assumption about constant length of the filling phase and alterable length of the aeration phase from 0 to 6 hours determines duration of the anoxic phase associated with mixing (T_M) within the range from 6 to 0 hours respectively. In practice, minimum length of the aeration phase during the cycle can be set at 2 hours and length of the anoxic phase (mixing) will be completion of that time to 6 hours ($T_M = 6 - T_{O2}$).

In order to determine the relationship between C,N,P removal efficiency and aeration phase length a series of computer simulations were carried out with different values of T_{O2} and at wastewater temperature of 6 and 14°C. Concentrations of C, N and P in wastewater were all expressed in COD units. Such an approach allows for using only one value in COD units to characterize concentration of all three elements in wastewater. The basis for expressing N and P content in wastewater in COD units is the reasoning that the discharge of T_N and T_P with effluent wastewater will generate some growth of biomass in the recipient through eutrophication (assuming that other elements are not limiting). As the change in biomass concentration can be expressed in COD units, discharge of a unit mass of N and P will cause some increase in the COD value in the recipient. For this research it has been assumed that 1 gN is equivalent to 12 gCOD and 1 gP is equivalent to 56 gCOD (Mikosz, 1999).

Discrete values of CNP removal efficiency obtained from the simulations were analyzed using non-linear regression methods. Plots of the continuous regression function

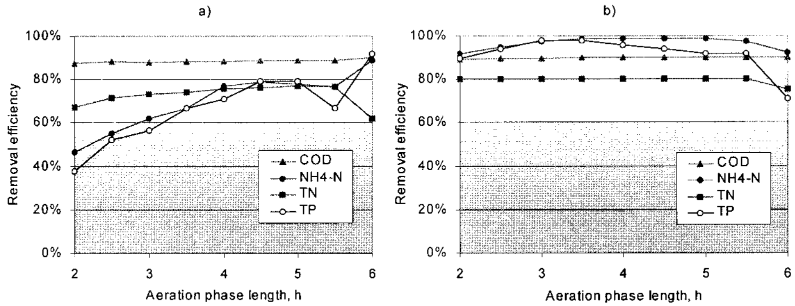

Figure 5 Simulated removal efficiency of CNP compounds in SBR in Nowy Targ WWTP at temperature 6°C (a) and 14°C (b) as function of the aeration phase length

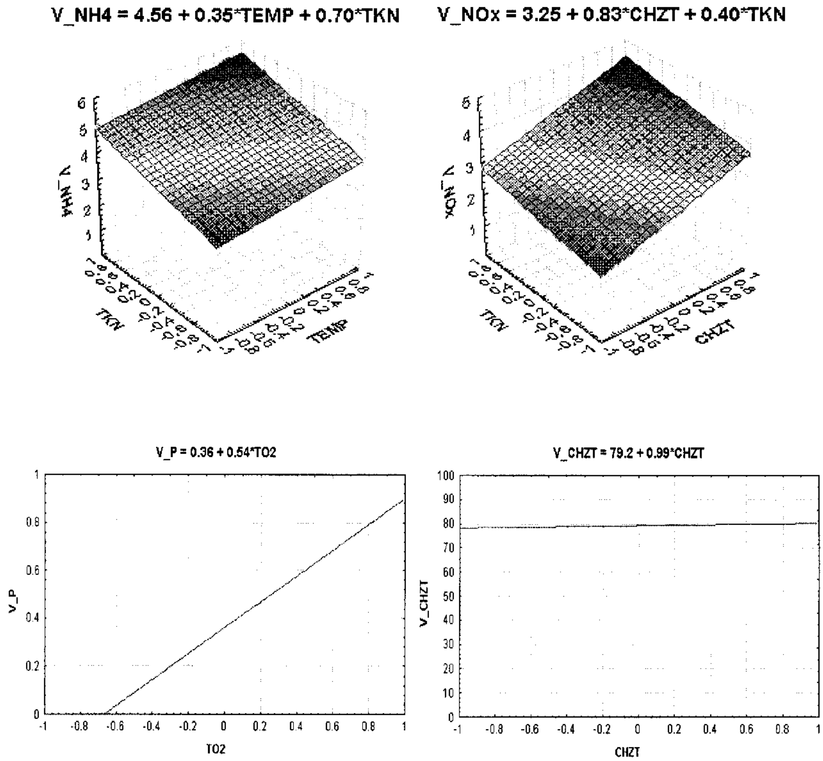

Figure 6 Simulated relationships of removal rates for organic compounds (V_{ChZT}), phosphorus (VP), ammonia nitrogen (V_{NH4}) and nitrates (V^{NO3}) as a function of COD and TKN in influent, wastewater temperature and length of aeration phase. (Note: $V_{ChZT} = V_{COD}$)

describing the relationship between CNP removal efficiency and aeration phase duration $y = f(T_{O2})$ at the confidence level 95% and for wastewater temperature 6°C and 14°C are shown in Figure 4.

The shape of the function shows that at 6°C the CNP removal efficiency increases with the duration of aeration phase and reaches its local maximum at $T_{O2} = 4.78$ h, which can be easily checked through calculation of the first derivative from the function. Observed increase in the CNP removal efficiency is caused mainly by the increase in efficiency of biological phosphorus removal and biological nitrification as is shown in Figure 5. At 14°C increasing duration of the aeration phase does not affect CNP removal efficiency as strong as at 6ºC. First the efficiency increases reaching its local maximum 88% at T_{O2} = 3.64 h, and then it gradually decreases down to 82% at T_{O2} = 6 h .

Sensitivity analysis

Sensitivity analysis was performed on the model of the new strategy for the SBR in Nowy Targ WWTP in order to get an overall picture of how the system will behave under varying external conditions. Input data to the model used during the analysis was identical to that used when simulating new operational strategy at 6ºC. Multivariate sensitivity analysis was performed using experiment planning method with independent variables transformed into normalized values (-1, +1), where (-1) relates to minimum value of a variable and (+1) relates to its maximum value. Independent variables included: wastewater temperature (*TEMP*) in the range +6 to +14ºC; COD in the influent (*ChZT*) in the range 300 to 900 mgO_2/l; soluble phosphorus in influent (SP) in the range 2 to 8 mgP/l; TKN in influent (*TKN*) in the range 25 to 60 mgN/l; duration of aeration phase (T_{O2}) in the range 2 to 6 hours. Dependent variables were defined as the rates of removal of COD (V_{CHZT}); ammonia nitrogen (V_{NH4}); nitrates (V_{NOx}); and phosphorus (V_P). The straight-line approximation functions' equations for each dependent variable obtained from the analysis are presented in Table 3 and graphically in Figure 6.

Conclusions

The major objective of the research carried on at Nowy Targ WWTP was to adjust the length and the structure of the SBR cycle under low wastewater temperature conditions and to forecast the expected technological effects of the new operational strategy. Based on the computer simulations the extension of the SBR cycle length from 6 to 8 hours and the aeration phase length from 2.75 to 5 hours were proposed. The proposed cycle structure is as follows:

- filling and mixing - 1 h
- filling and aerating - 1.66 h
- aeration (reaction) - 3.34 h
- sedimentation - 1 h
- decanting - 1 h

Extension of the SBR cycle length by 2 hours will decrease the hydraulic capacity of the Nowy Targ WWTP by about 25%. This is why the 8 h SBR cycle should be implemented in fall and winter when hydraulic load of the plant is smaller and wastewater temperature is low.

The results of the simulation show that the extension of the aeration phase from 2.75 to 5 h under low wastewater temperature conditions (6ºC) will raise efficiency of biological nitrification (from about 50% to 80%) and biological phosphorus removal (from about 45% to 75%). The effect of this change on biological denitrification will be smaller – T_N removal efficiency will increase from about 70% to 80%, and there will be no change in organic compounds' removal efficiency. Introduction of the 8 h cycle and extension of the aeration phase practically will not affect CNP removal efficiency at 14ºC, causing only a small increase in nitrification efficiency.

Based on the results of the simulations a modification of the SBR operational strategy at the Nowy Targ WWTP is planned in winter. It will allow for practical verification of the research.

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