EXPERIENCE IN NITROGEN REMOVAL - THE CASE STUDY OF THE KUJAWY WWTP, KRAKÓW

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ABSTRACT:
The research works on biological removal of nitrogen has been initiated at the Kujawy WWTP, in Kraków in 2003, as a consequence of more restricted nitrogen effluent standards; the new nitrogen effluent concentration has been set at 10 g N/m^3. The results of the initial research investigations helped to identify some reasons of limited nitrogen removal at the plant. They included in order of importance: characteristic of wastewater entering the bioreactor, especially a very low level of easily biodegradable organic compounds (the BOD_5/TN rate holds back denitrification), adverse impact of supernatant and lower activity of activated sludge at a low anoxic bioreactor volume (25 % of the total volume). Since there was more than one cause that hindered the increase of nitrogen removal, the following strategy was accepted, that allowed for a gradual elimination of particular causes. At the same time, both a continuous supervision of the plant operation and adjustment of preliminary assumptions were employed. Once the technological modifications were introduced, the nitrogen removal reached over 80 % , mostly due to better denitrification efficiency. However, such performance did not guarantee a continuously stable performance, therefore a further analysis of technological solutions and operation conditions was continued to intensify denitrification. It comprised: (a) utilization of biodegradable organic materials present in raw wastewater by employing additional processes, enhancing their hydrolysis in wastewater and sludge; (b) proper management of supernatant generated at the sludge treatment line; (c) dosing of an additional substrate.

KEYWORDS: denitrification, nitrogen removal, biological treatment, wastewater,

INTRODUCTION

A need of intensification of the biological nitrogen removal process had become an urgent problem at the Polish wastewater treatment plants in recent years. Most of the average- and large- size plants received new discharge permits, where the effluent total nitrogen concentrations were limited to more stringent values. Some plants still operate according to more liberal „transit permits", which offer the possibility to upgrade the technological lines to comply with new regulations, but at the same time this goal has to be reached as soon as possible. The troubles with nitrogen removal efficiency occur also at the plants that meet the new standards but their operation conditions do not guarantee a stable performance.

Such problem exists at the Kujawy WWTP in Kraków. The plant had been designed and commissioned at the time where more liberal effluent standard were enforced. Moreover, its construction lasted so long that, to cut down the investment costs, the facilities built in the early stage of construction had to be lately adapted to match the final design of a treatment train. Additionally, the capacity of the wastewater treatment plant had to be increased in recent years, due to reorganization of the Kraków sewer system; an additional sewage volume from the central Kraków was directed via the Dolna Terasa Wisły (DTW) channel to the Kujawy WWTP.

PROCESS CHARACTERISTICS

Project background

The Kujawy WWTP accepts wastewater from the Nowa Huta district; a combined sewer system prevails in this area. According to the preliminary project assumptions, the plant capacity was designed as 110 000 m^3 d^{-1}. For this capacity construction works were carried out and 4 parallel wastewater treatment trains were completed. In years 1996-97, the final design was prepared to verify an actual wastewater balance. At that point, it was proposed that the plant would be constructed as a two-phase project, with the phase I capacity of Q = 70 000 m^3 d^{-1} (Banaś et al., 2001). It was also decided that only 3 out of 4 trains would be furnished with the process equipment. In the course of the equipment mounting another change was made: the surface aerators, selected previously for activated sludge aeration, were substituted with the submerged aerators FRINGS, supplied with compressed air. In the years 2009- 2010 subsequent modernization of the Cracow and Nowa Huta sewer systems was carried out (a new DTW channel) that resulted in the further increase of a wastewater flow to the Kujawy WWTP.

Plant description

The plant flow diagram is presented in Figure 1. Wastewater is collected throughout the city and enters the plant through the main – its size: 250 cm x 350 cm. During a rainfall, an overflow of excess wastewater can be bypassed to the effluent line, both ahead of the plant (dilution higher then 1 + 3) and downstream of the primary clarifiers (dilution higher then 1+ 1). Wastewater passes (by gravity) coarse screens (1), aerated grit chambers (2), fine screens (3) and is pumped (4) via an overpass channel to a distribution chamber. Then the flow splits into pressurized lines, which transport wastewater to 4 technological trains; each train comprises one primary clarifier, D = 42 m (5), biological reactor (3 phase-BARDENPHO) (6) and two secondary clarifiers, D = 42 m (7). The plant has a coagulant dosing installation for a supplementary simultaneous phosphorus precipitation, if required. The effluent is discharged to the river in an open channel, furnished with the flow measuring equipment.

A sludge processing line includes: separate thickening of primary (gravity thickeners) and waste (mechanical thickeners) sludge, anaerobic sludge digestion and mechanical sludge dewatering in belt presses. Supernatant is pumped back to the head of the plant.

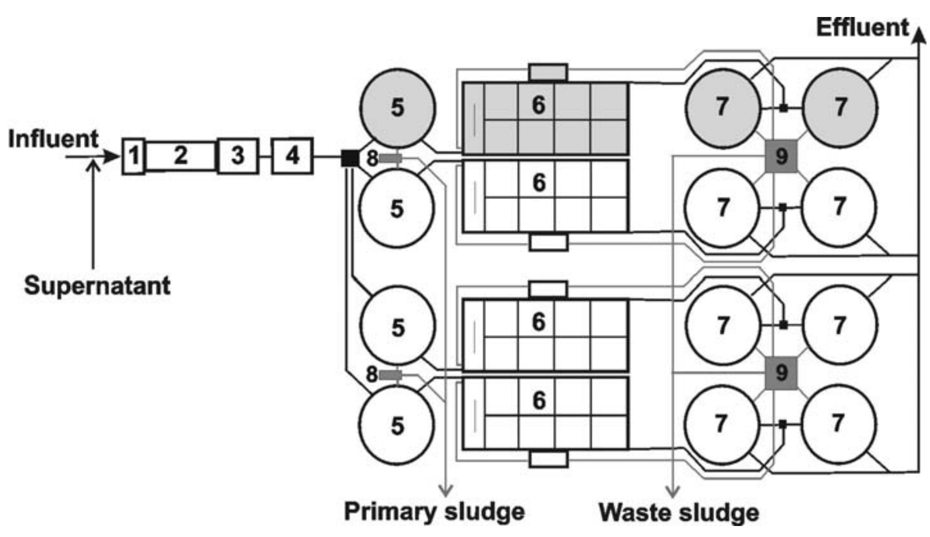

Figure 1. Flow diagram of the Kujawy WWTP, Kraków (Styka & Beńko, 2005)

OPERATION CONDITIONS

Construction of biological reactors

The biological rectors at the Kujawy WWTP were designed as a 3- phase BARDENPHO-process. A single reactor comprises: anaerobic circulation-type tank, two anoxic tanks, four completely mixed aeration tanks and an internal recirculation channel. Since surface aerators (AP) were recommended during the design, then tank configuration followed the guidelines of the Polish unified system UNIKLAR (KNAP). The main disadvantage of this system was tank shape that became too shallow near the outer walls. The AP aerators were mounted on the poles that uphold working platforms. In the last phase of the project the aeration system was upgraded and instead of surface aerators, FRINGS submerged aerators, type 2400 TRG with a motor N_S= 22 kW were used. Compressed air of pressure Δp = 3 mH_2O was supplied by the air pipe coming from the central blower building; the air pipe was mounted on the special landing. An increase of pressure ahead of an ejector increases the air volume supplied to the aeration tank, though the range of increase becomes rather limited, as it turned out during plant operation. Once the limiting air volume is reached, the air bubbles diameter gets larger and the efficiency of this mixed-type aeration system decreases. The range of a mixing zone was not sufficiently analyzed during the aerator selection process. According to the manufacturer's specification the range for the aerator TRG 2400 is defined by the tank diameter ΦA = 8 m, where mixing is intense and ΦB = 16 m, where mixing is just acceptable.

The Cracow University of Technology was engaged in the plant technological start-up. Its research works (Banaś & Styka, 2001) focused on: determination of an oxidation capacity of FRINGS aerators, examination of aeration conditions in the nitrification tank, oxygen profile in reactors, nitrogen transformation and biological phosphorus removal. The research showed that the oxidation capacity OC of the aeration system is compatible with the manufacturer's specification, in standard conditions. Examination of oxygen profiles along the nitrification tank helped to discover anaerobic zones and different oxygen concentrations along the tank's depth. Oxygen concentrations decreased sharply with tank's depth confirming its inadequate mixing. The main reason of a lower operation OC was poor mixing in tanks constructed according to the UNIKLAR system. For instance, in the tank with two aerators 25% of a tank surface was poorly agitated, while in the tank with only one aerator – 50%. This seems to be the principal cause of lower OC in operation conditions. Another cause is a relatively small depth of the tank close to its walls and the poles, located next to aerators, where streams responsible for air/water mixing are very intense. Technological calculations showed that there was also the third reason for a low OC - too high diffusion coefficient α was applied during aerator selection. The coefficient is never equal or larger than 1, as it was mentioned in the tender documents delivered by the manufacturer; usually its value is approx. 0,7. Too low dissolved oxygen concentrations discovered at the plant during the start-up procedure, caused by a lower OC of submerged aerators, and poor mixing conditions resulted in operation problems. Insufficient oxygen supply to biological reactors forced operators to run a biological process at very low sludge concentrations.

Biological nitrogen removal

Preliminary investigations conducted by the Cracow University of Technology in years 2003-2004 identified some reasons of poor nitrogen removal, if compared with the perspective requirements The following reasons were identified, that limited the process efficiency:

- shortage of organic substrate for denitrification due to characteristic of wastewater entering the bioreactor, especially low concentrations of easily-biodegradable organic compounds combined with an unfavorable BOD_5/TN ratio; another reasons included supernatant management and high efficiency of primary clarifiers performance,

- operating conditions in bioreactors, mainly a low sludge activity resulting in: presence of dissolved oxygen in recycled sludge and a low anoxic volume of the bioreactor.

Strategy of technological changes proposed to intensify the nitrogen removal process comprised the following actions:

- Hydrolysis/disintegration of organic compounds coming from internal carbon sources to change an unfavorable structure of organic compounds in wastewater. The process was tested both for wastewater and sludge. Generation of easily- biodegradable organics from the primary sludge seemed to be a promising solution at high sedimentation efficiency, observed at the Kujawy WWTP. The actual configuration of technological train allowed for hydrolysis in so called „active settlers" only; other solutions involving sludge disintegration would require further investments.
- To reduce a negative impact of supernatant the authors proposed its separation and utilization of organic compounds from gravity thickeners supernatant; these compounds are desired in biological processes while in the previous technological scheme volatile fatty acids present in these streams were lost. Efficient utilization of volatile fatty acids required re-direction of supernatant from gravity thickeners directly to the reactors. Other supernatant streams would be stored and then slowly and gradually discharged to the treatment train, mainly at low nutrient concentrations in raw wastewater. Total elimination of supernatant would require its individual treatment in an additional treatment line.
- Higher BOD_5/TN ratio after modification of primary clarifiers operation. A lower efficiency of primary clarifiers required shorter retention times so one primary clarifier was taken out of operation, though such operation was rather difficult to run. Then, each of 3 technological trains operated with only one primary clarifier and there was no possibility to regulate a flow volume between the primary clarifier and the reactor. Taking off any of clarifiers required modification of pipe arrangement that would enable to split wastewater flow to different reactors. Raw wastewater could also be delivered directly to reactors, by-passing primary clarifiers.
- Larger volume of anoxic chamber. Since the reactor was divided into separate chambers with walls, only step- changes were possible that resulted in V_D/V_R of 38 %, if one aerobic chamber was turned into anoxic one, or 50 %, if such change was done for 2 aerobic chambers.
- Higher internal recycle rate; it required a change of equipment or supplementary pumping mixers.
- Intensification of biomass activity and sludge inventory in reactors using a higher organic loading in the reactor. Low sludge organic loadings resulted in a low sludge activity, a low fraction of live heterotrophic bacteria and a high fraction of nitrifiers. Higher loadings were possible due to different characteristic of wastewater entering each of technological trains, a lower number of operated sewage trains and lower sedimentation efficiency. Since there were some limitations in oxygen supply to the reactors, larger sludge inventory and its higher loading could only be introduced gradually with a simultaneous control of aerobic conditions in the reactors. Regardless of the attempted actions related to reactor organic loadings, aeration system improvements had a positive effect on the nitrogen removal process; the aeration system was considered as a major limitation in modification of technological regime.

TIMETABLE OF THE PROPOSED CHANGES IN TECHNOLOGICAL REGIME

Within the framework of the proposed strategy some changes were suggested. Their goal was to rationalize the current technological system, without unnecessary investment costs. The following technological changes were proposed; here they are presented in a chronological order (graphical presentation in Fig. 2 , red color):

- Gradual reduction (from March 2004) of hydraulic loading in the wastewater train no. 3, until 15 % of the total raw wastewater flow was reached. This way hydraulic loadings of the remaining trains increased over 40 %. Such operation resulted in: increase of sludge concentration in reactors, increase of a unit sludge yield, higher activity of activated sludge and change of its structure.
- Along with a higher sludge loading in the reactors (March 2004) an installation was built that directed supernatant from primary sludge gravity thickeners directly to reactors no. 1 and 2. Such solution made possible utilization of volatile fatty acids, which are valuable organic substrates in biological processes.
- Increase of anoxic chamber volumes in reactors no.1 and 2 (reactor no. 1, August 2004; reactor no. 2 September 2004) from 25 % to 38 %. Such operation was performed by turning off aeration in the first currently operated aerobic chamber and substituting it with mixing. Until the modified chambers were furnished with mixers, mixing proceeded with just one aerator, without compressed air supply.
- To increase an oxygen supply to the reactors, the aerators removed during previous operation were replaced into initial aeration chambers (September 2004).
- Some attempts were taken to limit settling efficiency by shortening a settling time and one of 3 primary clarifiers was taken out of operation (September 2005). The existing pipe lines between primary clarifiers and biological reactors made impossible an even distribution of wastewater between 3 reactors. Wastewater downstream of one primary clarifier was divided evenly into biological reactors no.1 and 2, while wastewater from the second clarifier went to reactor no 3. Troubled operation of such treatment configuration, mainly during torrential rains, made this technological change difficult to maintain. Therefore, though it was beneficial for nitrogen removal efficiency, the original configuration with the third clarifier had to be restored; at least until a new channel connecting effluents from all clarifiers is constructed and put into operation.

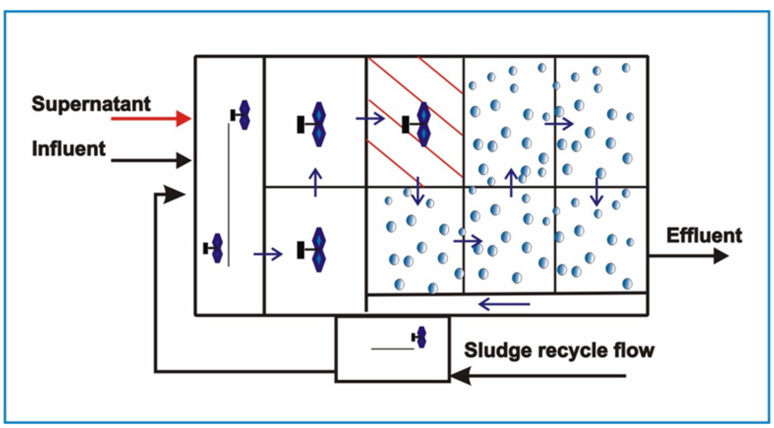

Figure 2. Layout of the Kujawy WWTP after changes introduced during the research

RESULTS – PLANT EFFICIENCY AFTER ITS MODIFICATION

After the above modifications had been introduced the reactor performance improved, mainly with respect to denitrification, though high efficiency of the remaining processes was also maintained. Once the changes were implemented, denitrification efficiency started to improve, while nitrification efficiency remained at a stable level.

The total nitrogen concentration dropped down below 20 g N/m^3 (Table 1) and the average nitrogen removal increased from 58 % to 70 % and then up to 80 %, once other technological corrections were introduced. In spite of an unquestionable improvement in a biological nitrogen removal process, it was still difficult to maintain throughout the whole year stable effluent concentrations that would satisfy the perspective requirements. Implementation of other technological changes such as: modification of primary clarification, changes of the anoxic chamber capacity in the reactor or generation of organic substrate from the internal sources was not possible without some technical alterations (a channel connecting effluents from primary clarifiers, expansion of a primary sludge pumping station), as well as an aeration system upgrade.

Due to the planned expansion of the municipal sewer system and therefore a larger capacity of the Kujawy WWTP, a full scale research on intensification of biological nitrogen removal was withhold until the new process conditions were established.

Table.1. Effluent quality at the Kujawy WWTP.

Parameter	X 2003	V-VI 2004	IX-X 2004	V-VI 2007	**VI-IX 2010**
BOD_5 (mg/l)	4,2	4,6		3,5	**2,8**
COD (mg/l)	26,1	23,6	22,9	22,0	**22,6**
TS (mg/l)	8,8	5,0		2,8	**3,3**
TN (mg/l)	21,3	17,7	13,7	9,7	**9,5**
TP (mg/l)	1,2	1,4	1,2	0,36	**0,2**

At the same time, a search for new technological solutions that would enable to further intensify biological nitrogen removal at the Kujawy WWTP was carried out, using the computer simulations (Beńko P.).

They showed that the most promising strategy of intensification would involve an increase of a COD/TN ratio in the influent to the biological reactor; such observations confirmed a great impact of an organic substrate supply on the nitrogen removal efficiency.

PLAN OPERATION AT INCREASED LOAD CONDITIONS

The expansion of the Krakow sever system was completed in years 2009/2010 (construction of the DTW channel). After expansion, some northern city districts as well as some Nowa Huta communities were connected to the plant. All that resulted in an increase of the average wastewater flow entering the Kujawy WWTP by 43% (Table 2) though the influent quality did not change considerably (Table 3).

Table 2. Average daily flow to the Kujawy WWTP

	Qd av [m^3/d]	
	before DTW connection 2009	**after DTW connection** 2010
Average	44 880	64 167
P = 50%	42 500	62 040
P = 65%	44 470	64 730
P = 85%	49 170	71 630
P = 90%	54 400	74 250

Table 3. Influent quality at the KUJAWY WWTP

Parameter	**before DTW connection** 2009	**after DTW connection** 2010
BOD_5 (mg/l)	330	292
COD (mg/l)	680	609
TS (mg/l)	326	269
TN (mg/l)	61,0	63,9
TP (mg/l)	7,3	6,6
COD/ BOD_5	2,1	2,1
BOD_5/ TN	5,4	4,6
BOD_5/ TP	45,2	44,2

A substantial increase of a wastewater flow resulted in higher organic loadings at the plant, if compared to the values observed in 2009; the observed increase of the average values was: for BOD_5 – 25 %, COD – 27 %, TS – 17 %, TN – 48 %, TP – 27 %.

Higher oxygen demand in biological reactors, as a result of higher organic loadings, had a negative effect on activated sludge performance, mainly nitrifying organisms. In summer, a stable performance was observed and the process efficiency remained high (Table 1), while in the other periods the nitrogen removal was very low.

At present, it is necessary that the technological train number 4 (currently not working) is furnished and put into operation. Also a replacement of aeration system with fine-bubble aeration is considered.

A number of computer simulations were performed with the BIOWIN program to model high organic loading conditions at the plant. A new model of a biological stage of the Kujawy WWTP was introduced, including capacities of all 4 operating technological trains and an ultimate wastewater quantity and quality. The values of kinetic and stoichiometric constants, functions and well as pollutant fractions were assumed as for the currently operating system.

The results of simulation carried out on the calibrated model of the biological stage of the Kujawy WWTP, at the ultimate conditions, showed that the capacity of 4 biological trains is sufficient to accept the ultimate organic loading in 2030. To further enhance denitrification efficiency a larger volume of reactor anoxic chamber $V_D/V_R = 0,5$ would be required..

To comply with the future effluent standards TN $\leq$ 10 gN/m^3 the Kujawy plant has to substantially increase an organic carbon concentration ahead of biological reactor. The estimated organic carbon value, at the assumed mass balance calculations, is approximately 80 gO_2/m^3.

RESULTS

- The experimental studies conducted at the Kujawy WWTP showed that it is possible for the plant to achieve high denitrification rates, quite sufficient to meet the effluent standards. However, the process is limited by biodegradable organics available in the reactor influent. Additionally, a larger anoxic volume in the reactor is required and the nitrification efficiency cannot be upset.
- The results of the study confirmed that the following modifications of the current treatment process conditions had to be done:
  - shorter retention times in primary clarifiers; long sedimentation results in undesirable changes of the BOD/TN ratio in wastewater. It is necessary to increase up to 80 gO_2/m^3 the concentrations of organic carbon ahead of the biological reactor
  - successive increase of the anoxic chamber volume up to 50% of the reactor volume; the increase should be accompanied with upgrading of the aeration system to assure successful nitrification,
- As a result of larger wastewater flow, the plant has to put in operation its 4-th technological train and furnish it with technical equipment. The results of computer simulations confirmed that denitrification performed better when the volume of anoxic chamber reached the ratio V_D/V_R = 0,5. However, it should be noted that there is a possible danger of nitrification collapse at such high V_D/V_R ratio and the minimum temperature of 12^{o}C. Therefore, it was proposed that a section of the anoxic chamber should be equipped with both aeration system and mixers, to maintain high nutrient removal efficiency. Such option would allow to occasionally lower the V_D/V_R ratio, if periods of minimum temperature occur.
- The required ecological effect with respect to total phosphorus is possible only when simultaneous phosphorus precipitation is applied.

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