Modern trends at natural and wastewater treatment plants reconstruction

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Abstract. This article discusses ways to intensify the natural water treatment plants operation using foamed polystyrene as a contact and filtering medium for bioreactors and filters. The reagent schemes with polystyrene foam filters are offered for the surface water treatment. The improved physicochemical and biological methods for slightly acidic and neutral groundwater preparation are recommended to use. The use of ferrobacteria metabolism products for the ammonium nitrogen oxidation in a slightly acidic medium was investigated. The x-ray spectral analysis of bio-minerals matrix structures was conducted. The reasons of unsatisfactory technical condition of sewage treatment plants in Ukraine were analyzed. The ways of increasing their work efficiency using sedimentation aerotanks of large hydraulic height and using the simultaneous nitrification-denitrification were offered.

I. Introduction

The provision of quality drinking water for the population and ecosystem preservation needs modern innovative solutions in the field of working plants reconstruction and building new water preparation and wastewater treatment plants [1].

The groundwater chemical composition is formed under the many natural and anthropogenic factors influence: temperature, \(O_2\) and \(CO_2\), pH and Eh, changes in routes, water levels and water consumption, microbial life and man-made load. Therefore, groundwater refers to complex multicomponent systems, characterized by different pH – Eh values, hydrocarbonate alkalinity, salt content, chromaticity, contain heavy metal ions, easily oxidizable organic compounds, humic acids, dissolved gases, and compounds containing nitrogen \(NH_4^+\), \(NO_2^-\), \(NO_3^-\), phenols, surfactants, phosphates, microflora.

The technogenic component of contaminations is based on the infiltration water inflow from the earth surface water and surface water reservoirs. It is known [2] that 80% of household wastewater drains are treated at mechanical and biological treatment plants which were built in 1960-1980. The technological equipment of such plants is outdated and worn-out and does not allow water to be treated to normative parameters. The wastewater treatment technologies require the innovative changes [1, 3-6]. This problem is especially acute in cities with population less than 200 thousand people, where the number of unsatisfactory treated wastewater is on average from 44 to 63% [2, 7]. It should also be noted that 43% of urban settlements and 97% of rural settlements do not have centralized wastewater systems.

The discharges of insufficiently treated urban and industrial wastewater, sludge storages, areas of sediment accumulation from household wastewater treatment plants, surface discharge wastewater from cities and industrial plants, which treatment requires the modern technologies introduction [3, 4] bring
the particular danger for the environment and for water sources. In particular, every year up to 40 million tonnes of sediment are accumulated at areas, which decomposition products gradually infiltrate the underground aquifers.

Considering that 24.0% of the main groundwater aquifers in Ukraine are classified as conditionally protected and another 36.0% is unprotected, the role of water treatment plants in the water supply systems of settlements is greatly increased and requires the modern integrated methods use [8, 9]. Therefore, a complex problem solution of sanitary and environmental rehabilitation in settlements through the reconstruction of working and building of new natural and wastewater treatment plants, using modern methods, resource saving and energy saving technologies and equipment, using modern mathematical modelling of processes are the urgent tasks of today [10-12].

2. Materials and Methods

We had conducted a long-term study of water preparation and wastewater treatment processes by experimental and theoretical methods. The plants for technological processes of water treatment research on a macro scale were used in the laboratory of the department of water supply, sewage and drilling (Figure 1) to get mode data and on a micro scale to obtain the model parameters. A considerable number of experimental data was accumulated during the inspection of the working treatment plants, in the commissioning process and long-term operation of the treatment plants which were reconstructed according our recommendations.

The titration, potentiometric and photocolorimetric methods in the certified laboratory of the department were used to determine the contamination concentrations in water. Moreover, the water physicochemical parameters were determined by independent certified laboratories. The electron microscopy of bio-minerals matrix structures samples was performed by X-ray spectroscopy analysis with a Quanta 200 scanning electron microscope (USA), equipped by a XDA spectrometer for microanalysis (EDAX). Water consumption was determined by ultrasonic flowmeters or by volumetric method.

The studies were carried out at the pilot plant (Figure 2) which included the 2000 dm³ inlet water tank (No 1), the 500 dm³ reaction flask (No 2), the Kamovskiy pump (No 6) for air pumping from the reaction flask and pumping the solution under block diagrams, flasks with removable paper filter “blue ribbon” and the ceramic filter (No 4), the MM-5 magnetic stirrer (No 3), the filtrate collection tank (No 5) and rubber hose systems that connected the separate compartments into the one technological scheme. The dissolved oxygen concentration was 0.5-0.8 mg/dm³.

The experiment planning and mathematical statistics methods using the MS Excel statistical package and the MathCAD appendix were used during the preparation and processing of experimental studies.

3. Results and Discussions

Our long-term experience has allowed us to develop a number of resource-efficient technological schemes for water treatment, both in new building and reconstruction the existing water supply and sewage systems. We recommend the polystyrene foam filters use, which are firstly proposed at the Department of Water Supply, Sewage and Drilling (NUWEE, Rivne) during water filtration at granular filters application. The polystyrene foam filter is a container with foamed polystyrene which is in flooded state with the help of the retarded net. Foam polystyrene medium is made directly at the water treatment plant by foaming the polystyrene product or produced at plants of thermal insulation boards in special foaming devices. The polystyrene foam medium can be single-layer or double-layer.

The floating foam polystyrene filters with ascending filtration are increasingly introduced into the practice of water treatment [13]. In a constructive way the floating foam polystyrene filters are easier than filters with heavy medium (sand, zeolite, etc.). The treated water is collected in the filtration space during the filtration and during washing such water moves downstream and washes the medium. It is enough to close the latch of outlet water supply and open the washed latch to the necessary value. As a rule, the distribution system is not arranged over the polystyrene foam medium and its functions are performed by the retaining net. The distribution system should be at the bottom of the filter: tubular with
round holes, hole or pipe with holes and additional sloping walls, only one hole with the outlet into the pipe at small filter sizes.

**Figure 1.** Laboratory plant for water iron removal at polystyrene foam filter with the increasing bed of suspended sediment a) filtering column; b) water preparation system with high iron concentration.

**Figure 2.** Scheme of the pilot plant for study the kinetics of the iron compounds oxidation in suspended sediment bed from bio-minerals matrices, iron bacteria and iron hydroxide.

The polystyrene foam filters can be used in two-stage reagent schemes for water clarification and discoloration for its final treatment after settling tanks or clarifiers with suspended sediment, or in one-stage schemes as contact polystyrene foam filters, at water iron removal schemes, for the surface water pretreatment, for the wastewater tertiary treatment [14].

First, the source water is carefully treated with sodium hypochlorite for the organic substances oxidation in reagent schemes of water clarification and discoloration and then the coagulant solution is introduced into the water to provide the hydrophobic particles coagulation.

The sorption medium bed should be filled up to remove odors and flavors into the underfilter space of the polystyrene foam filter, forming a polystyrene foam-carbon filter so. Sorption capacity of coal AG-3 allows using it without regeneration up to one year. High uniformity of coal AG-3 provides favorable hydraulic modes of filters operation, especially during washing.

The aeration and subsequent filtration is recommended to use for water iron removal with sufficient alkalinity and high pH. The ordinary polystyrene foam filter is used in the outlet water (Figure 3) at the small iron ions concentration, and at high iron ions concentrations, it is used with a growing suspended sediment bed and polystyrene foam medium [14].
The reconstruction of water iron removal plants with low alkaline reserve and low pH is another perspective direction of work intensification by the biochemical treatment method in complex with physicochemical methods (Figure 4) [15]. The biochemical oxidation method application is made possible by the widespread distribution of ferro-bacteria in groundwater in different regions of the world [16-18].

So, the treating process was completed within 35 minutes at slightly acidic groundwater treating under laboratory conditions with cations \( \text{Fe}^{2+} \) 3.0-3.6 mg/dm\(^3\) concentrations and sediment volume of 1 cm\(^3\) (Figure 5, curve 1). The value pH of 6.2 and hydrocarbonate alkalinity to 2.5 mmol/dm\(^3\) increasing was occurred with the soda ash solution of 10 mg/dm\(^3\) addition that resulted to the biochemical processes intensification by an average of 20% and the completion of the process within 25 minutes (Figure 5, curve 2). The kinetics of \( \text{Fe}^{2+} \) cations removal from the solution coincides with the kinetics of the process at adding the soda ash solution of 10 mg/dm\(^3\) to the system at the hydrocarbon alkalinity value increasing in the system to 3.7-3.8 mmol/dm\(^3\) (Figure 5, curve 3).

**Figure 5.** Kinetics and efficiency of weakly acidic and neutral groundwater treatment with the cations concentration of \( \text{Fe}^{2+} \) 1.6-3.6 mg/dm\(^3\) in the matrix structures bed of ferro-bacteria depending on the contact time and inlet water quality parameters:
1– pH 5.5; The alkalinity 0.8 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 3.6 mg/dm\(^3\); 2 – pH 6.2; The alkalinity 2.5 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 3.6 mg/dm\(^3\); \( \text{Na}_2\text{CO}_3 \) 10 mg/dm\(^3\); 3 – pH 6.8; The alkalinity 3.74 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 3.0 mg/dm\(^3\); 4 – pH 6.0; The alkalinity 1.0 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 3.0 mg/dm\(^3\); 5 – pH 7.4; The alkalinity 3.4 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 3.0 mg/dm\(^3\); \( \text{Na}_2\text{CO}_3 \) 10 mg/dm\(^3\); 6 – pH 7.1; The alkalinity 3.4 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 1.6 mg/dm\(^3\); 7 – pH 7.1; The alkalinity 3.4 mmol/dm\(^3\); \( \text{Fe}^{2+} \) 1.8 mg/dm\(^3\).

The analysis of the formed matrix structures of bio-minerals was achieved due to the X-rays diffraction, light and scanning electron microscopy (SEM). Consideration of the general spectral analysis data (Figure 6) shows that a large number of O, N, C, Al, Si, and Fe atoms are present in the sediment. The carbon atoms and nitrogens presence testified about the biological component of the bio-minerals matrix structures.

The \( \text{Al}^{3+} \) \( \text{Fe}^{3+} \) ions presence has aroused an interest in terms of the metals adsorption process with variable valence. Metals were electrostatically bound to both the anionic surface of the cell wall and the organic polymers that were exuded by the cells on the outside and accumulated on their developed surface. The white impregnations were observed on the catalytic film surface considering the electronic images, which are surface-adsorbed matrix structures of Al compound, which accents the structure activity to the metals adsorption from the water environment [19].

The ammonium nitrogen removal in bioreactors can be represented by several mechanisms, depending on the water quality parameters and the microorganisms’ qualitative composition in
groundwater and in contact medium of the bioreactor. The process of NH$_4^+$ ions sorption on the matrix structures surface of bio-minerals and on the bacteria cells can be considered in neutral and near neutral groundwater with the hemolitoautotrophic bacteria of the genus Gallionella presence, due to the presence of functional groups: PO$_4^{3-}$, COO$^-$, OH$^-$ on their surface, which is confirmed by our X-ray spectral analysis of matrix structures.

Figure 6. X-ray spectral analysis of the granule surface of filtering medium at the water treatment plant, which works by combined biological and physicochemical methods.

The following mechanism for the ammoniacal nitrogen with hydroxyl radicals `OH interaction which are formed in the system according to the Fenton reaction is possible at underground slightly acidic waters treatment, containing genus Lertothrix bacteria in contact medium of the bioreactor

$$\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \text{OH}^- + \text{OH}^-.$$  

(1)

With the reaction of dissolved ammonium nitrogen presence in underground ferruginous waters, it is also possible to oxidize it with hydroxyl radicals formed as a result of the bacteria activity of the genus Leththrix, by the mechanism [20]:

$$\text{[NH}_4^+ + \text{OH}] \rightarrow \text{[NH}_2 + \text{H}_2\text{O}_2] \rightarrow \text{[NHOH]} \rightarrow \text{[NO}_2^-] \rightarrow \text{[NO}_3^-]$$  

(2)

The dissolved organic compounds (RH) oxidation, in particular lightly oxidized organic compounds, also was recorded during our study at natural groundwater due to technological schemes: bioreactor-filter; bioreactor – liming – coagulation – filtration. The their oxidation mechanism in a weakly acidic environment with the Fe$^{3+}$ ions, ferrobacteria, peroxide hydrogen, hydroxyl radicals presence can be described by the following chemical reactions

$$\text{`OH} + \text{RH} \rightarrow \text{H}_2\text{O} + \text{R}^-,$$  

(3)

$$2\text{OH}^- \rightarrow \text{H}_2\text{O}_2,$$  

(4)

$$\text{R} + \text{H}_2\text{O}_2 \rightarrow \text{ROH} + \text{OH}^-,$$  

(5)

$$\text{R} + \text{O}_2 \rightarrow \text{ROO}^-,$$  

(6)

$$\text{ROO}^- + \text{RH} \rightarrow \text{ROOH} + \text{R}^-.$$  

(7)

The unsatisfactory technical condition of wastewater treatment plants creates a significant technogenic danger for Ukraine groundwater aquifers, as was noted above. Mainly this is the result of the long duration of their exploitation and imperfect technologies, with the use of materials and equipment, which quality does not correspond to the wastewater aggressive nature. The reconstruction of such wastewater treatment plants usually involves the outdated equipment replacement to newer, which responds to modern requirements, the implementation of planned or major repairs of individual facilities.
In particular, increasing the efficiency of large waste removal from wastewater is carried out by installing mainly filtered step grilles that are widely produced by industry. Their small transparency which increases the retarded waste amount and the easy waste removal from wastewater with the subsequent pressing possibility are the peculiarity of such grilles.

The use of the aerated grit chambers is an effective method of the increasing sand retention by 1.5 times. In addition, it provides a low content of organic impurities in the retarded sediment, its ash content is 5-10%. Aerated grit chambers can be used to retain fats, petroleum products and as a biocoagulator at the excess active sludge adding. In addition, the wastewater aeration is also provided.

The most effective method to improve the primary sedimentation tanks work is to add reagents into the wastewater. However, such technology use requires the additional mixers construction, flocculation chambers and reagent facilities. Conversion of primary sedimentation tanks to biocoagulant mode with the excess activated sludge addition or biofilm allows the additional removal of organic pollutants from wastewater due to biosorption. There is a positive experience of combining settling processes in one settling tank with subsequent separation of the suspended solids together with excess activated sludge by flotation (Flotation biocoagulation). Conversion of primary sedimentation tanks into flotation biocoagulators allows to reduce the primary wastewater treatment duration up to 30-40 min, and to reduce BODs of wastewater entering into the aeration tank by 30-40%. At the same time, there is also a decrease in concentrations of detergents, fats, petroleum products of heavy metal ions and other contaminants. The moisture content of the removed flotation sludge is 94-96%. In recent years, thin-layer blocks of polymeric materials have been effectively used to intensify the initial sedimentation at the treatment plants reconstruction. Thin-layer blocks can significantly increase the wastewater treatment plants productivity and at the same time to increase the suspended solids retention efficiency.

One of the most effective methods of increasing the aeration tanks oxidizing power is to increase the mass of sludge involved in wastewater treatment process. The activated sludge mass increasing can be achieved by three methods. The first method is carried out in aeration tanks with fixed or moving-bed to increase the concentration of biomass (MBBR, “vija”, “cleaning glass brush”). The second method provides sludge mixes separation at special filter partitions or membranes (MBR). The third method involves the separation of concentrated sludge mixture by thin-layer sedimentation tanks, pressure flotation cells or applying secondary settling tanks of large hydraulic height.

The growth of the sludge mass requires an increase in oxygen supply in the aeration tanks for the endogenous respirations needs. In the aeration tank with a high concentration of activated sludge the aerators with high oxidizing ability, mechanical, pneumatic-mechanical and jet aerators can be used. However, mechanical and pneumatic-mechanical aerators have significant disadvantages; they are the insufficient degree of mixing volume aeration zone; the limited capacity of the working area of one aerator; the special equipment to service the aerators; the low reliability because of possible damage to the engine or gearbox; the possible water pollution for grease lubrication. The main disadvantage of jet aerators is small penetration depth in sludge mixture flow of the working liquid captured air bubbles. However, the rational organization of flow in jet aeration tank can successfully provide mixing sludge, as evidenced by their positive experience with long-term use in many wastewater treatment plants.

At the wastewater treatment plants reconstruction is important to increase the productivity of wastewater sludge stabilization and dewatering facilities. For example, increasing of aerobic digesters productivity can be achieved by their work transferring into autothermophilic mode. At the aerobic digestion of sludge with less than 95% humidity the amount of heat released in the decay of volatile part organic matter is sufficient for self-heating of the sludge to a temperature of 55-65°C. As a result, the duration of the process is reduced in several times, and therefore the productivity of existing facilities increases. Due to the nitrifying bacteria death, the demand for oxygen is reduced and the sludge is pasteurized. The heat of the heated sludge can be utilized.

The transfer of sludge fermentation process into digesters from mesophilic to thermophilic mode allows to increase their productivity by about two times. It is advisable to supply the resulting gas to cogeneration units to produce heat and electricity.
The most effective devices for mechanical sludge dewatering in our time are filter presses and dehydrators.

The implementation of the above measures allows increasing the efficiency of wastewater treatment, but cannot guarantee the maintenance of modern requirements for the quality of treatment in principle, mainly for the nitrogen and phosphorus compounds content [2]. In practice, two technologies are commonly used, MLE (modified Ludzak-Etinger process) and A2O (anaerobic-anoxic-oxic process), which have been proven for many years and are reliable in exploitation. The first technology also involves the phosphates reagent removal and the second involves the treatment with the biological removal of nitrogen and phosphorus compounds. The facilities are calculated according to the ATV-131E standards.

The practical implementation of these technologies in the reconstruction of existing wastewater treatment plants can be carried out in two ways (Figure 7). The first way involves the arrangement of anaerobic, aerobic and anoxic zones on the basis of individual existing elements of the wastewater treatment plant, primary or secondary sedimentation tanks, aeration tanks, etc. In the anaerobic and anoxic zones, the mixing of the sludge mixture should be carried out using electromechanical stirrers.

The second way is advisable to use at high treated wastewater consumptions and large sized aeration tanks. In this case, it is advisable to arrange the aerobic and anoxic zones in the aeration tanks by constructing a vertical partition that will divide the volume of the aeration tank into two parts by the oxidation ditches type. In this case, it is advisable to circulate the sludge mixture using electromechanical mixers and aeration by one or more sections arranging with aerators at the bottom.

The treatment facilities of the meat processing plant are an example of modern technologies use at the wastewater treatment plants reconstruction (Figure 8). The aeration tank of high hydraulic height with surface jet aeration was used for biological wastewater treatment in this case. The effective ammonium nitrogen removal by simultaneous nitrification-denitrification is occurred due to the formation of the aerobic zone in the upper part of the aeration tanks and anoxide zone in the lower part [2].

4. Conclusions
It is possible to conclude, that the presence of such factors as the multicomponent nature of natural and wastewater, with the impurities ability to change their phase-dispersed state under the influence of physical and chemical factors, allows the wide range of techniques and methods use for the water treatment plants reconstruction based on the analytical review results and our own theoretical and experimental studies results. The most suitable methods, processes and apparatus choice should be conducted using the following current trends in the field of natural water and wastewater treatment:

- it is recommended to use foamed polystyrene of different fractions as contact medium of bioreactors and filtering medium of clarifying filters;
- the foam polystyrene filters may be used in the natural surface water tertiary treatment in two-stage reagent schemes after settling tanks or clarifiers with suspended sediment;
- the aeration method with the next filtration on polystyrene foam filters is recommended to use to purify groundwater from low concentrations of iron ions, sufficient alkalinity and pH. It is advisable
to use a combined technology with a growing suspended sediment bed and polystyrene foam medium at the high concentration of iron ions;

- to use a complex of biological and physicochemical methods for purification for the treatment of aggressive weakly acidic and near neutral groundwater with low alkaline reserve;

- to conduct the correction of the pH-Eh values of the medium, the value of hydrocarbonate alkalinity, the concentration of inorganic carbon by adding a soda ash solution to activate biological processes of iron removal in bioreactors, which allows to improve the treatment efficiency up to 30%;

- the ferrobacterial metabolism products ($\text{H}_2\text{O}_2$, $\text{O}^*$, $\text{OH}^*$) use for ammonium nitrogen oxidation and easily oxidizing organic compounds in a weakly acidic medium on the matrix structures surface in the pore space of contact bioreactors medium;

- using the ability of bio-minerals matrix structures to adsorb metal ion with variable valence;

- the conversion of primary sedimentation tanks into flotation biocoagulators mode allows to reduce BOD$_5$ of wastewater with simultaneous decreasing concentrations of detergents, fats, petroleum products of heavy metal ions and other contaminants.

- it is recommended to use MBBR and MBR type bioreactors to increase the aeration tanks oxidizing power by the activated sludge mass increasing;

- it is possible to use technologies MLE and $\text{A}_2\text{O}$ during the reconstruction of existing wastewater treatment plants, which allow for simultaneous removal of nitrogen and phosphorus compounds.

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