Wastewater Treatment Modeling Using Combined System Bio-Filter With Activated Sludge

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الخلاصة

الغرض من هذه المقالة هو تقييم إمكانيات إزالة النتروجين والفوسفات لتعزيز إزالة المركبات البيولوجية في محطة معالجة مياه الصرف الصحي باستخدام النترجة المنفصلة على الأغشية الثابتة. استند التحليل على محاكاة عدة متغيرات للنظام المدمج: أداء الحمأة المنشطة بالغشاء الثابت. تم استخدام موديل الحمأة المنشط ASIM 2d المرتبط بموديل تحولات الملوثات في الغشاء الثابت. أجريت نتائج التحاليل وفقاً لمعايير المدخلات: المعدل اليومي لمياه الصرف الصحي، درجة الحموضة، المتطلب الكيميائي للاوكسجين، قيم العوالق الصلبة الكلية، النتروجين الكلي، نيتروجين النيترات، الفوسفور الكلي، والقلوية. أشارت النتائج إلى إمكانية تضمين الغشاء الثابت في تكنولوجيا الحمأة المنشطة لتحسين إزالة النيتروجين والفوسفور من مياه الصرف الصحي. تم إجراء عملية النترجة في غشاء ثابت، في حين تم تنفيذ إزالة النيتروجين والفوسفور من مياه الصرف الصحي في غرف الأكسدة التي تعمل بتقنية الحمأة المنشطة. تضمن عملية ازالة النتروجين والفوسفات الى هبوط مستوى الفوسفور بنسبة (81٪)، ولكن فقط إذا استهلكت الكائنات الدقيقة الموجودة في حجرة الأكسدة بسهولة الطبقة التحتية القابلة للتحلل وإذا كانت هناك نترات كافية.

الكلمات المفتاحية

مياه الصرف المنزلي، الحماة المنشطة، الاغشية الثابتة، ازاله النترجة، ازالة الفوسفات، النموذج الرياضي.

Abstract

The purpose of this article is evaluation of the possibilities of using denitrifying dephosphatation to enhance biogenic compounds' removal in the wastewater treatment plant with separated nitrification on fixed-film. The analysis was based on the multi-variant simulations of the combined system: fixed film activated sludge performance. Activated sludge ASIM 2d model related with the model of pollutions transformations in fixed film was used. The results of exploitation analyses were performed according to the input parameters: average daily rate of wastewater, pH, COD values, total suspended solids, total Kjeldahl nitrogen, nitrate nitrogen, total phosphorus and alkalinity. The results indicated that there is a possibility of including fixed film in the activated sludge technology in order to improve nitrogen and phosphorus removal from the wastewater. Nitrification process will be performed in fixed-film, whereas nitrogen and phosphorus removal from the wastewater will be performed in anoxic chambers which operate in the activated sludge technology. Denitrifying dephosphatation process guarantees the high level of total phosphorus reduction (81%), but only if the whole easily decomposable substrate will be consumed by microorganisms in the anoxic chamber and if enough nitrates will be present in the environment.

Keywords

Household wastewater, Activated sludge, Fixed-film, Denitrifying, Dephosphatation, Mathematical model.

1. Introduction

Wastewater treatment plants which were put into operation in the late (70s and 80s) of (20^{th}) century do not fulfill the normative requirements any more, particularly regarding biogenic compounds removal [1]. Treatment plant modernization means liquidation of biofilters. Normally a designer does not see the possibility of including biofilters into biological dephosphatation scheme coupled with nitrification and gentrification. Possibility of integration biofilters and activated sludge to intensify biogenic compounds removal from the wastewater occurred when bacteria capable of denitrifying dephosphatation were identified [2,3]. Bacteria that accumulate phosphates may be divided into two groups: bacteria that accumulate phosphates from wastewater with oxygen as an electron acceptor and with nitrites as electron acceptors [4,5,6,7,8,9]. The first one belongs to classic anaerobic-aerobic system whereas in the second case phosphorus is removed in anaerobic48 anoxic zones. Denitrifying dephosphatation allows for elimination of oxygen chamber. In such system competition between microorganisms is directed towards predomination of bacteria capable of dephosphatation in anoxic conditions. By avoiding unnecessary aerobic usage of organic compounds, denitrifying potential of the system increases and enables effective wastewater dephosphatation with low BOD_5/P ratio. Closing dephosphatation in anaerobic-anoxic cycle allows for separation of nitrification and dephosphatation system, and conducting it on isolated biofilters or on separate part of activated sludge [10,11,12]. Dephosphatation can be also effective when nitrites act as electron acceptors. However they cannot occur in to high concentration due to their inhibiting influence on process of excessive phosphates intake by microorganisms, which continues even after cessation of NO_2-N dosage into the sludge. According to Huang et al. (2015), critical concentration of nitrite nitrogen in anoxic chamber should not exceed (5-8) mgN-$NO_2 \cdot dm^3$ [13]. Separation of nitrification beyond the traditional system leads to increasing the percentage of nitrifiers in biomass, thus increase in productivity of this process [14,15]. Introduction of nitrification on biofilters into activated sludge systems allows for more effective nitrogen removal in low temperatures without necessity of increasing volume of oxygen chamber [16,17,18]. Removal of higher amount of organic compounds in anoxic conditions stands for deeper denitrification and in consequence reducing energy consumption for aeration and lower production of excess sludge. Process of denitrifying dephosphatation is possible in flow and cyclically operating systems. Research on denitrifying dephosphatation in SBR reactor carried out by Styka (2004) showed that due to introduction of anoxic phase in the middle of aerobic phase in anaerobic-aerobic SBR reactor with quick filling, fraction of denitrifying bacteria PAO (Phosphate Accumulating Organisms) increased from (16 to 44%) of the total number. DEPHANOX system is an example of practical realization of nitrification separated on biofilter in a flow system [19]. This system reduces general phosphorus by (71%) with 7.8 mgP·gsmo^{-1}·d^{-1} of its intake, whereas efficiency of nitrate nitrogen reduction reached about (60%) with (30) mgNO_3-N·gsmo^{-1}·d^{-1} speed of the process. DEPHANOX system also contributed to improvement of sludge sedimentation capacity (sludge index equaled ml·g^{-1}) [20,21,22]. The objective of the paper is to evaluate possibilities of removal of biogenic compounds using denitrifying dephosphatation process in a treatment plant with nitrification separated on biofilters. This evaluation was carried out on the basis of data from one of municipal wastewater treatment plants in Kuala lumpur Malaysia, in which only trickling filter technology is currently used as a biological component.

2. Material and methods

Results of municipal wastewater treatment obtained in exploited mechanical-biological wastewater treatment plant in kualalumpur-Malaysia were the basis for performed calculations. Wastewater from about (14) thousand of citizens runs into the treatment plant. The designed wastewater treatment plant capacity equals (8620) m^3/d. The following objects are included into the technological chain of the analyzed treatment plant: horizontal sand separator with manual sand removal, two Imhoff's primary settling tanks, two submerged anoxic filters filled with BIOPEX packages (currently out of exploitation), two I stage trickling filters filled with quartzite break stone of 80 m^2·m^{-3} active surface, three vertical intermediate settling tanks, II stage sewage pump station, three II stage biofilters (two with quartzite break stone filling and one filled with BIOPEX packages), coagulant PIX dosing station and two II stage secondary settling tanks (vertical and radial) as shown in Fig.(1). In determining the configuration of each variant of modernized in the future technological chain of wastewater treatment a principle of maximum use of objects, which already exist in the treatment plant, and minimum dosage of chemicals was applied. Computations were carried out for five technological variants as shown in Fig. (2).

Differences in variants I-V result from adopted values of anoxic chamber volume and oxygen concentration. In general, wastewater treatment processes in the discussed variants run as follows: after initial treatment in primary settling tank wastewater goes to anaerobic chamber where orthophosphates are released by bacteria cells. Energy to obtain and converse substrates (easily decomposable organic carbon) into polyhydroxyalkanoates, mainly poly-β- hydroxybutyrate, accumulated in PAO microorganisms' cells is derived from hydrolysis of cell polyphosphates. Subsequently, wastewater runs into intermediate settling tank, where residue is separated in sedimentation process. Supernatant rich in orthophosphates and ammonium nitrogen with small amount of organic matter is transferred to trickling filter, in which nitrification of ammonium nitrogen occurs.

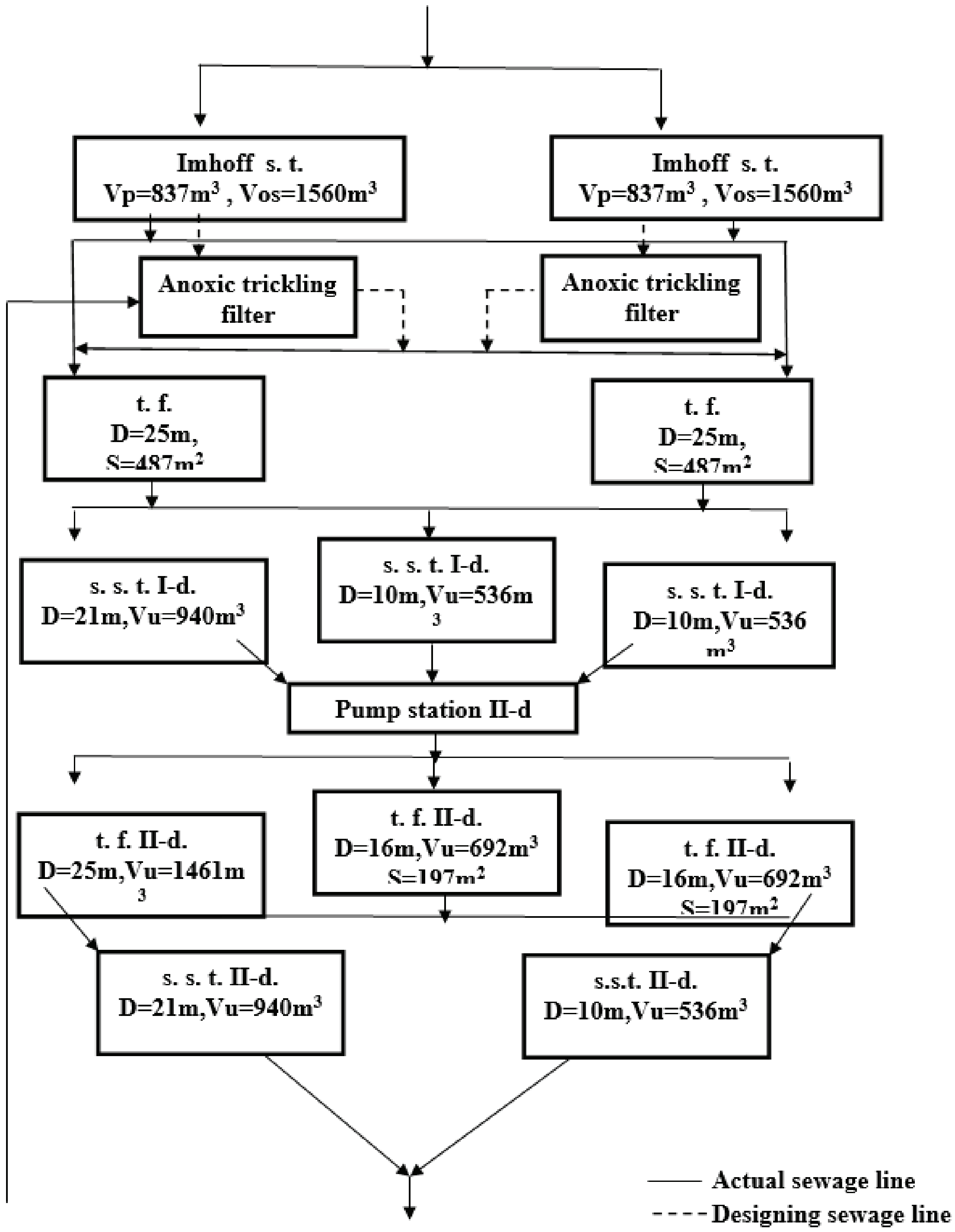

Fig. (1) The exploited technological chain of the analyzed wastewater treatment plant: Imhoff s. t. - Imhoff settling tank; t. f. - trickling filter; s. s. t. I-d. - secondary settling tank first degree; Pump station II-d. - Pump station second degree; t. f. II-d. - trickling filter second degree; s. s. t. II-d. - secondary settling tank second degree

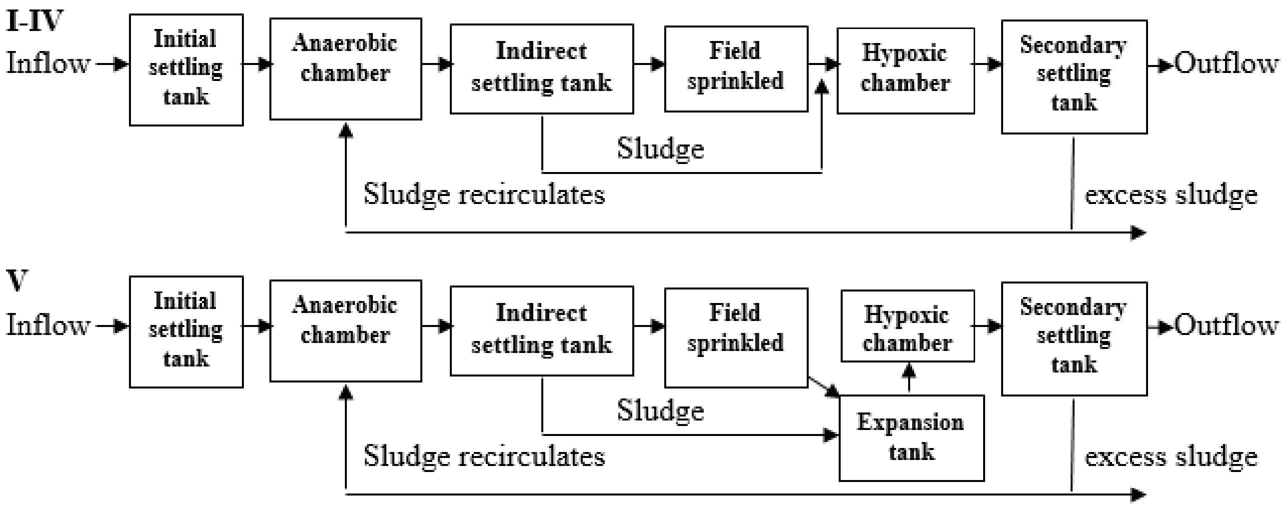

Fig.2 The technological variants of the wastewater treatment plant facilities, included in the variant calculations.

Sediment from the intermediate settling tank with PAO bacteria is transported to anoxic chamber to which also nitrified wastewater from biofilter, rich in nitrates, flow in. In anoxic chamber with low oxygen concentration and presence of nitrates as electron acceptors excessive intake of dissolved orthophosphates with simultaneous denitrification of nitrates takes place. The last element of the system is the secondary settling tank in which activated sludge is separated from the treated wastewater by sedimentation. Treated wastewater runs into the collector and sludge is partially recirculated to anaerobic chamber, while the remainder is discharged outside the system as the excess sludge.

Table (1) compares technical parameters of devices included in the analyzed variants. Equipment from the mechanical part of the wastewater treatment plant, II stage of bio filter with BIOPEX packages filling, intermediate and secondary settling tanks from the previously exploited technological chain were left for operation, but I and II stage filters filled with quartzite break stone will be eliminated. Two existing chambers with submerged beds, which currently are not exploited, will be adapted as anaerobic chamber. In proposed variants anoxic chamber will be a new object created within modernization efforts.

Table (1) Technical characteristics of devices included in the analyzed variants

Device	Device characteristics				
Variant	I	II	III	IV	V
Primary settling tank	Settling tank volume V = 837m^3; Depth of the flow part H = 2.5m; Amount of sludge/wastewater = 0.20; hydraulic load O_h = 13.44 m^3·m^2·d^{-1}				
Anaerobic chamber	Oxygen concentration O_2 = 0.0 mg·dm^3; Chamber volume V = 100 m^3; Retention time T_h = 0.4 h.				

Intermediate settling tank	Amount of sludge/wastewater = 0.60
Trickling filter	BIOPEX packages; Specific surface A = 150 $m^2 \cdot m^3$, Filter volume V = 1460 m^3, Oxygen concentration O_2 = 2 $mg \cdot dm^3$
Anoxic chamber	Volume Volume Volume Volume Volume 400m^3 400m^3 1000m^3 1000m^3 600 m^3 O_2 = 0.8 O_2 = 0.5 O_2 = 0.8 O_2 = 0.5 O_2 = 1.0 $mg \cdot dm^3$ $mg \cdot dm^3$ $mg \cdot dm^3$ $mg \cdot dm^3$ $mg \cdot dm^3$ Depth H=4m Depth H=4m Depth H=4m Depth H=4m Depth H=4m
Secondary settling tank	Volume V = 1880 m^3; Depth H= 4 m; Hydraulic load O_h = 9.74 $m^3 \cdot m^2 \cdot d^{-1}$; Sediment load O_o = 4.77 $kg \cdot m^{-2} \cdot d^{-1}$; Amount of sludge/wastewater = 0.20; Reactive settling tank

Although it was assumed that in anoxic chamber denitrifying dephosphatation will occur, dissolved oxygen concentration was accepted to range from (0.5 to 1.0) $MgO_2 \cdot dm^{-3}$ for additional intake of phosphates remaining in the wastewater by microorganisms. Calculations of pollution removal capacity in analyzed variants of technological chain were based on commonly used mathematical models of pollutants transformation in bioreactors with activated sludge and bio filters. In recent years such attitude is more and more common in simulation of exploited treatment plants as well as in designing new technological systems of treatment. Processes related to wastewater treatment can be predicted using artificial neural networks (ANN), where the number of input variables can be separated by cluster analysis [23,24] or by the principal component analysis [25,26]. Models ASIM (Activated Sludge Simulation Model) widely discussed in literature, where the researchers are leading in the modeling issues of operation of systems with activated sludge [27,28, 29,30,31,32,33]. In the present work, the activated sludge chambers were based on ASIM 2d model. This model represents continuation of the previous version called ASIM 2 [34,35,36]. It takes into account dissolved substance which consists of fermentation products, wastewater alkalinity, very easily and easily decomposable organic matter, nitrogen dioxide as denitrification product, ammonium and ammonium nitrogen, nitrite and nitrate nitrogen, dissolved oxygen and inorganic phosphates. This model also includes non-dissolved substances, such as: nitrifying organisms, heterotrophic aerobic and facultative anaerobic organisms, indecomposable molecular organic substance, salts and metal hydroxides included in processes of chemical phosphorus precipitation, PAO phosphate accumulating bacteria, cell components of bacteria e.g. poly-β-hydroxybutyrates, polyphosphates, slowly decomposable hydrolysed organic substances and general suspended solids [37]. ASIM 2d model considers (21) unitary processes qualified into (5) groups of: hydrolysis, processes with heterotrophic bacteria, processes with autotrophic bacteria, polyphosphate accumulating bacteria and chemical processes. Mathematical description of denitrification processes with polyphosphates accumulating bacteria was included in this model. Simulative calculation of activated sludge chambers was realized using BioWin 2 software [38]**.** To realize the objective of the research, model of pollutants' transformation on biofilter, described in Rauch's et al. (1999) was also included in ASIM 2d model [39]. This model consists of the following assumptions: biological membrane is of homogenous structure and density throughout the depth, microorganisms are uniformly distributed in the biological membrane, reactions occur with first-order kinetics and dissolved substances are immediately diffused by biological membrane. Transformation of organic matter and nitrification of ammonium nitrogen in biological membrane were calculated according to the scheme given by Henze et al. (2002) [40]. Results of exploitation research on the objective treatment plant, which included: average daily wastewater inflow, pH reaction, COD values (total and dissolved), total suspended solids, Kiejdahl's general nitrogen, nitrate nitrogen, general phosphorus and alkalinity were adopted as input parameters for calculations. Wastewater composition was determined by referential methods stated by standards [40]. Analyses of total and dissolved COD content (after filtering through a filter of (0.45) µm pore size in raw wastewater were performed and then share of each fraction was defined according to methods described by Henze et al. (2002) [40]. Life time of sludge was at 10 d and constant temperature at (T = 20ºC.) Constants of reaction kinetics were implemented from the range given by Henze et al. (1999) [41]; therefore, the obtained results can only illustrate the potential possibility of adaptation the existing biofilters into chain with activated sludge. All simulations were performed in set conditions.

3. Results and Discussion

3.1 Technological chain of wastewater treatment plant

The main reason why variant calculations of technological chain of the wastewater treatment plant were undertaken was because the treated wastewater did not meet conditions from the water law permission for the objective treatment plant for general nitrogen and phosphorus concentrations, which was confirmed by the statistical analysis of the obtained outcomes. The results showed that concerning BOD_5 values correctly for (66.2%) of year, COD = (99.4%), total suspended solids = (98.6%), general nitrogen = (3%) and general phosphorus = (89.8%). Considering insufficient capacity of wastewater treatment concerning removal of biogenic compounds, variant deliberations were carried out to search for optimal solution of technological chain which would guarantee reliable operation of the object, regarding nitrogen and phosphorus removal from the wastewater and would also enable maximum usage of the existing objects. Classical technological systems with activated sludge need to modify in order to intensify the process of biogenic compounds removal [40]. Table (2) presents average values of each COD fraction in raw wastewater, which were used for modeling. Dissolved COD fraction constituted less than (21%) of total COD whereas share of decomposable (dissolved and molecular) organic substances equaled (82%) in total COD.

Table (2) COD fraction in wastewater running into the treatment plant.

COD fraction	Value, mg/dm^3
Dissolved decomposable S_{BS}	110.53
Dissolved indecomposable S_{US}	34.54
Molecular decomposable S_{BP}	456.92
Molecular indecomposable S_{UP}	89.81

It suggests that the analyzed wastewater is susceptible to biochemical decomposition. Table 3 shows average values of the analyzed pollution indexes in the treated wastewater obtained in performed calculations compared to values gained from the exploitation of the existing technological chain. Variants I – IV lower treatment capacity was obtained for organic matter in comparison to the existing object. BOD_5 values were significantly higher than the admissible level of (15) mg $O_2 \cdot dm^{-3}$. However, it was observed that increase of anoxic chamber volume from (400 to 1000) m^3 and increase of oxygen concentration from (0.5 to 0.8) mg $O_2 \cdot dm^{-3}$ causes increase of organic pollutants' reduction. It results from the fact that although nitrified wastewater after biofilter with low amount of organic pollutants flows into the anoxic chamber, it is still overloaded with organic matter from the residue after intermediate settling tank. Calculations showed that the average BOD_5 value in the sludge was (1117.9) mg $O_2 \cdot dm^{-3}$, and COD (2550.3) mg $O_2 \cdot dm^{-3}$.

Table (3) Capacity of selected pollution indexes observed in exploited technological chain and calculated for analyzed variants.

Pollutants character	RWW	Removal efficiency of TWWTP* (%)	Removal efficiency variant (%)				
			I	II	III	IV	V
BOD_5 (mgO2$\cdot$dm^{-3})	267.01	95	83	81.5	89	88	96

COD($mgO_2 \cdot dm^{-3}$)	690.83	92	90	88	92.5	91.5	95
TSS ($mg \cdot dm^{-3}$)	209.23	91	98.5	99.5	99.5	99.5	98
General nitrogen ($mg \cdot dm^{-3}$)	62.37	58.5	70	70.5	72	73	42
General phosphorus ($mg \cdot dm^{-3}$)	9.03	62	65	65	66	68	81

*Treated wastewater of treatment plant

High load of sludge with organic substances causes increase of oxygen demand. Keeping low oxygen concentration in anoxic chamber causes substrate to be only partially mineralized which results in low BOD_5 and COD production. It also results from low activity of activated sludge in anoxic chamber. The calculated respiration speed for variants I and II ranged from (0.12 to 1.25) mg $O_2 \cdot gsm^{-1} \cdot h^{-1}$, and for variants III and IV (7.54 and 9.67) mg $O_2 \cdot gsm^{-1} \cdot h^{-1}$, respectively. For total suspended solids obviously higher reduction is observed in variants I-IV in comparison to the one obtained in the existing object. In each variant concentration of total suspended solids in the outflow was lower than the admissible value of (35) $mg \cdot dm^{-3}$. Introducing anoxic chamber after nitrifying filters contributes to increase of removal of general phosphorus from wastewater. It is mainly caused by significant ammonium nitrogen reduction in the wastewater in the nitrifying filter and its slight increase in anoxic chamber.

3.2 Nitrogen and phosphates Removal calculations

Clear nitrate nitrogen reduction resulting from classic dissimilative denitrification is not observed Fig.(3). In variants I-IV general nitrogen concentration in the outflow is significantly lower than the one obtained in the real object, however in each case the admissible value of (15) $mg \cdot dm^{-3}$ is exceeded. In variants I-IV significant improvement of phosphorus removal in comparison to the existing treatment plant is not observed. Average concentrations of general phosphorus obtained from the calculations are slightly lower than the real values for the analyzed object and exceed the admissible value of (2) $mg \cdot dm^{-3}$.

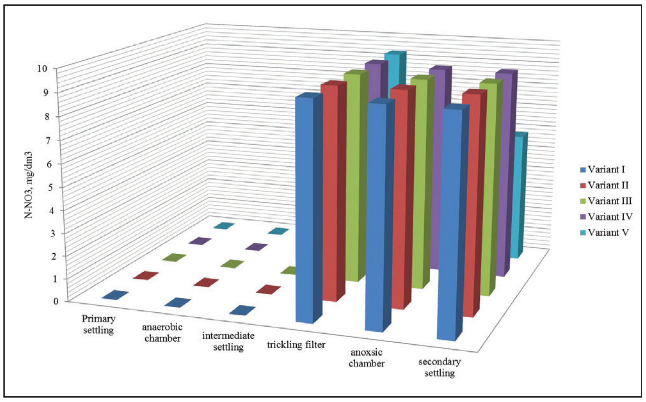

Fig. (3) Profile of concentration values of nitrate nitrogen for analyzed calculation variants.

It is worth noting, that phosphorus is removed only biologically in the analyzed variants, whereas in the existing treatment plant it is removed by chemical precipitation with PIX coagulant, dosed at the inflow to the II stage secondary settling tank. Therefore, possible modernization of technological chain carried out accordingly to the discussed variants would contribute to lowering the costs of wastewater treatment. Together with increase of anoxic chamber volume and decrease of dissolved oxygen concentration from (0.8 to 0.5) mg $O_2 \cdot dm^{-3}$ increase of consumed phosphates can be noticed as shown in fig. (4). Considering the fact that in anoxic chamber nitrate nitrogen occurred in concentration of about (9) mg $N\text{-}NO_3 \cdot dm^{-3}$, there was a possibility of denitrifying dephopsphatation, because $N\text{-}NO_3$ was electron acceptor for PAO bacteria. On the other hand, speed of phosphorus intake in anoxic chamber could have been be limited by insufficient nitrate. Phosphates were partially consumed by PAO bacteria when initial concentration of $N\text{-}NO_3$ equaled (25) $mgN\text{-}NO_3 \cdot dm^{-3}$, whereas practically total phosphates intake occurred with initial $N\text{-}NO_3$ concentration of (60) $mgN\text{-}NO_3 \cdot dm^{-3}$ and lasted until their complete depletion. COD/N ratio confirms nitrates deficiency for denitrifying dephosphatation. Optimum value of this ratio should amount (3.5) g COD/gN. With ratio higher than the given one (in the analyzed wastewater it was 11.1) incomplete phosphorus removal occurs, caused by deficiency of nitrates [42,43,44].

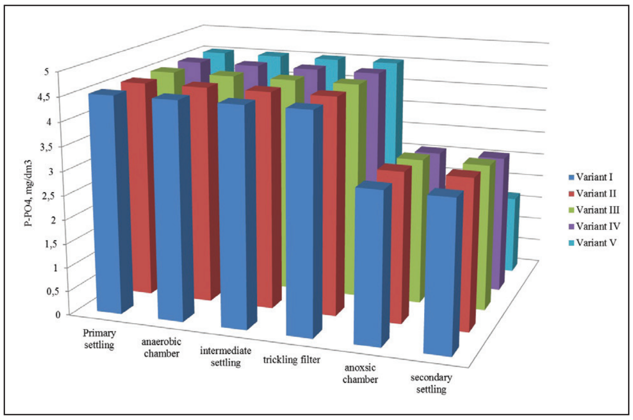

Fig. (4) Profile of concentration values of phosphates for analyzed calculation variants.

In variant V volume of anoxic chamber was decreased to (600) m^3 and oxygen concentration was increased to (1) mg $O_2 \cdot dm^{-3}$. As a result, significant improvement in organic pollutants removal was observed in comparison to variants I-IV. Average BOD_5 and COD values at the outflow from the secondary settling tank were lower than the admissible value defined in the water-law permission. Concentration of total suspended solids slightly increased at the outflow in comparison to previously analyzed variants. General nitrogen reduction was significantly worse and its average concentration at the outflow reached (36.44) $mg \cdot dm^{-3}$ and clearly exceeded value obtained in the existing object and admissible value from the water law permission. This situation is mainly caused by significant increase of $N\text{-}NH_4$ concentration in anoxic chamber to the level of (26.14) $mgN\text{-}NH_4 \cdot dm^{-3}$. Increasing of oxygen concentration in anoxic chamber caused decrease of denitrification process, which in turn caused increase of general nitrogen concentration at the outflow of the treatment plant. At the same time, such action caused increase of phosphorus consumed by PAO bacteria (general phosphorus concentration at the outflow of the settling tank was (1.74) mg $P_{og}\cdot dm^{-3}$ and does not exceed the admissible value. In anoxic chamber bacteria do not have organic acids to their disposal so only organisms capable of using stored, easily decomposable substrates exclusively in presence of nitrates as an electron acceptor are promoted [45].

4. Conclusion

The use of biofilters as biological stage in wastewater treatment plant exhibits a significantly removal of organic pollutants (BOD_5, COD) and total suspended solids. General phosphorus may be removed only by chemical precipitation. There is a possibility of including biofilters into activated sludge technology in order to improve nitrogen and phosphorus removal from the wastewater. Nitrification process will be carried out on biofilters, whereas in anaerobic and anoxic chambers operating in activated sludge technology process of nitrogen and phosphorus removal will take place. Separation of nitrifiers from heterotrophic organisms causes lack of competition between these organisms and higher stability of nitrifiers population. In systems with nitrification in so called"side sequence" denitrifying dephosphatation process will be possible. Using of denitrifying dephosphatation process reduces energy consumption of the system related to decreased oxygen need. Calculations showed that even with oxygen concentration of (1) $mgO_2\cdot dm^{-3}$ in anoxic chamber, denitrification as well as orthophosphates' intake were carried out by microorganisms. It results from the fact that PAO bacteria can use oxygen as well as nitrates as electron acceptors. Effective biological phosphorus removal is also possible, therefore amount of chemicals used for the process may be reduced Denitrifying dephosphatation process guarantees high general phosphorus removal at (81%) provided that total easily decomposable substrate will be consumed by microorganisms in anaerobic chamber and that sufficient amount of phosphates will be available. Calculations showed that integration of biofilters with activated sludge in flow system allows for high reduction of organic pollutants, total suspended solids and biogenic compounds from the wastewater. Considering general nitrogen reduction, the most favorable variant was the system with anoxic chamber (1000) m^3 in volume and oxygen concentration equal to (0.5) $mgO_2\cdot dm^{-3}$, whereas for phosphorus removal the solution with anoxic chamber (600) m^3 in volume and oxygen concentration of (1) mg $O_2\cdot dm^{-3}$. ASIM 2d model seems to be extremely useful tool for designing and simulation of wastewater treatment plant operation. It follows from the fact that it enables simulation of most processes occurring in bioreactor with activated sludge. This model considers mathematical description of denitrification processes with phosphate accumulating bacteria.

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