UDC 628.35
DOI: 10.15587/1729-4061.2017.107127

OXYGEN REGIME IN RESEARCH ON THE WORK OF PLUGFLOW AERATION TANKS WITH FIXED BIOMASSES

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Наведена математична модель сумісного вилучення органічних забруднень зваженим і закріпленим біоценозом в аеротенках-витискувачах і на основі її реалізації запропоновані методи розрахунку кисневого режиму при біологічному очищенні стічних вод. При цьому розглянуто можливі технологічні і конструктивні схеми в аеротенках-витискувачах: коли реактор, що містить елементи з закріпленим біоценозом, розташовано першим по напряму руху стічних вод та навпаки

Ключові слова: аеротенк-витискувач, кисневий режим, органічні забруднення, активний мул, біоплівка

Приведена математическая модель совместного извлечения органических загрязнений взвешенным и прикрепленным биоценозом в аэротенках-вытеснителях и на основе ее реализации предложены методы расчета кислородного режима при биологической очистке сточных вод. При этом рассмотрены возможные технологические и конструктивные схемы в аэротенках-вытеснителях: когда реактор, содержащий элементы с прикрепленным биоценозом, расположен первым по направлению движения сточных вод и наоборот

Ключевые слова: аэротенк-вытеснитель, кислородный режим, органические загрязнения, активный ил, биопленка

1. Introduction

Sewage treatment is one of the topical issues. Among the many ways and methods of purification, biological purification methods based on the use of microorganisms to oxidize (dispose of) organic contaminants are the most acceptable. These pollutants in wastewater are in the form of predominantly dissolved substances and are a source of nutrition for microorganisms. The process of biological purification from pollutants occurs in aerotanks under direct contact of sewage with an optimal amount of microorganisms of active sludge in the presence of an appropriate amount of dissolved oxygen [1–3].

However, applied in most sewage treatment plants, traditional technologies of biological treatment in modern conditions do not provide efficient and reliable purification of wastewater.

Therefore, research that is aimed at improving the efficiency of aeration facilities and obtaining a mathematical description of the processes of biological wastewater treatment is quite important.

2. Literature review and problem statement

In modern systems of biological wastewater treatment plants, the main building is a bioreactor-aerotank. In aerotanks, there happens a removal (biooxidation) of suspended (freely flowing) or dissolved organic pollutants (OPs) in water by means of active sludge that is perched on floating flakes. However, in connection with the increased requirements for the quality of water cleaning, the aerotank in such a system requires further improvement [4].

The efficiency of removing contaminants in aerotanks can be greatly enhanced by installing additional loading, on the surface of which a biofilm with a high concentration of microorganisms is formed. In this case, installation of additional loading (grids, nozzles, etc.) is assumed to be integral along with the suspended biocenosis (active sludge) in the volume of the construction [5, 6].

Mechanisms for the removal of OPs by active sludge are thoroughly investigated and described in published papers such as [7, 8]. The removal of OPs by a fixed biocenosis in the form of a biofilm has recently been widely investigated under filtering the purifying fluid in droplets and flooded filters. In this case, the dynamics of the biofilm formation on the loading surface and the mechanisms of OP removal by using it are considered and studied in [9–11].

In particular, the removal of OPs by microorganisms of a biofilm involves the need for additional consideration when cleaning OP mass transfer processes. It is also very important to take into account oxygen in the biofilm and through the boundary layer of the liquid that is formed on the surface of the biofilm, especially with the formation of the active part of the biofilm on the top of the filters.

In paper [12], a general mathematical model for extracting organic pollutants from sewage through droplet biofilters is described as substantiated and constructed. The model takes into account the interaction of hydraulic, physicochemical and biological processes when filtering through different loadings.

Combined biological treatment of sewage in structures with fixed and suspended biocenosis has a number of significant technological advantages. Namely, the aeration facilities that use a group of frozen and immobilized microorganisms have the following advantages [2, 6]:

– the ability to maintain a high concentration of active biomass in the volume of the structures without lowering the quality of the treated wastewater, because only the suspended part of the active biomass comes to the secondary sedimentation tank;

– high oxidizing capacity per unit volume of treatment plants and improved cleaning efficiency;

– high stability of the biological treatment system as well as stability under volley loads and the influence of toxicants;

– the possibility of an efficient flow of the processes of OP biodestruction, nitrogen denitrification, and biological removal of phosphorus compounds in one treatment plant due to the high concentration of the biomass, its significant phase, and various oxygen conditions throughout the biological film.

Thus, it is possible to ensure a high level of purification, i. e., the conditions of the necessary significant wastewater treatment, by installing a load with a fixed biocenosis in an aerotank.

The existing theoretical developments are based on implementing simplified approaches (models), which so far have failed to reflect a number of important components of water purification [12, 13]. The parameters of the biofilm, the hydrodynamic peculiarities of the receipt of organic pollutants and oxygen in the biofilm, the velocities of the kinetic reactions with the joint removal of organic contaminants by weighed and fixed biocenoses have not been taken into account sufficiently. As shown by the analysis conducted with the use of the existing research data, the failure to consider these factors significantly affects the obtaining of reliable calculation results [14]. At the same time, ASM-models take into account the peculiarities of the biological treatment process to a greater extent. However, such models are very complex (of a large dimension and a large number of parameters). Therefore, the identification and research of these models cause insurmountable difficulties [15].

Consequently, a sufficient level of aerobic sewage treatment can be achieved by in-depth research of complex mechanisms and various processes occurring in the volume of a bioreactor-aerotank. These processes are related to the formation of a biofilm of various thickness and structure on the surface of an additional loading (mesh) in the aerotank volume. In this case, it is very important to provide enough oxygen for the process of biochemical oxidation (utilization) of organic pollutants and to justify which of the components (pollutants or oxygen) limit this process.

For a more complete study of the mechanisms and peculiarities of the influence of the processes that occur in biofilm and in the volume of aerotanks with a mixed biocenosis in wastewater treatment, it is necessary to consider more complete and reliable mathematical models. Only such models can help obtain more reliable engineering methods for calculating the structural and technological parameters of bioreactors.

Taking into account the aforementioned, for the further substantiated intensification of aerobic wastewater treatment of organic pollutants in aerotanks, the development of more advanced and reliable methods for calculating the basic parameters of the process based on implementing more general mathematical models is a prerequisite.

Meanwhile, it is very important to take into account the mechanisms of the course of removing OPs by a biofilm that is formed on the surface of an additional loading and a suspended biocenosis (active sludge) in the volume of the aerotank.

3. The aim and objectives of the study

The aim of the study is to develop more sophisticated and reliable methods for calculating aerobic wastewater treatment in plugflow aerotanks with additional biomass attached and taking into account the oxygen regime.

To achieve this aim, the following objectives need to be solved:

– to present in general terms the basic equations and dependencies describing the biological purification process in plugflow aerotanks with additional attached biomass;

– to justify simplifications, which will allow receiving analytical dependencies for the possibility to develop engineering calculations;

– to consider possible variants of reactor arrangement with attached biomass.

4. Materials and methods of research on biotreatment in plugflow aeration tanks with fixed biomasses

It is known that depending on the hydrodynamic regime of the fluid flow, bioreactors-aerotanks are divided into mixer aerotanks and plugflow aerotanks [1–4, 7]. In modern conditions, methods of calculating aerotanks-mixers have been developed more thoroughly in comparison with the insufficient use of mathematical modeling for plugflow aerotanks, although the latter have significant technological advantages in the treatment of sewage.

In both cases, the removal of organic pollutants (OPs) occurs in aerobic conditions, i. e., through the consumption of oxygen necessary for the oxidation of OPs. Therefore, it is important for the existing aeration technologies to provide such an oxygen regime in a reactor in which the kinetics of the purification reaction will not be limited by the oxygen contained in the reactor.

In this case, there are significant differences in the technologies of oxygen (air) supply in the volume of a mixer aerotank and a plugflow aerotank. There are also features of its consumption by suspended (active sludge) and fixed (biofilm) biocenoses. An assessment and analysis of the oxygen regime in the mixer aerotank on the basis of implementing a mathematical model is considered in [16]. A mathematical model of the oxygen regime is constructed and implemented during OP removal in a plugflow aerotank with suspended and fixed biocenoses, which is described in the general case by the following equation:

$$\varepsilon\frac{\partial C}{\partial t}=D_l\frac{\partial^2 C_a}{\partial x^2}-\upsilon\frac{\partial C}{\partial x}+\varepsilon\alpha K_c a\left(\beta C_p-C_a\right)-\frac{F_{\delta l}}{W_p}N_c-R_{ac}. \qquad (1)$$

In practical calculations, it is enough to consider equation (1) in stationary conditions, and after evaluating its members, taking into account the known diffusion criterion of Péclet $Pe = \frac{\upsilon l}{D_l}$ for further implementation, we present it in the given form

$$-\upsilon\frac{\partial C_a}{\partial x} + \varepsilon\alpha K_c a\left(\beta C_p - C_a\right) - \lambda_c N_c - R_{ac} = 0, \quad (2)$$

$$N_c = -D_c\frac{\partial C}{\partial z} = K_c\left(C_a - C|_{z=0}\right),$$

$$\lambda_c = \frac{F_{\delta l}}{W_p} = \frac{F_\delta}{F},\ \ F_\delta = \frac{F_{\delta l}}{l},\ \ C|_{z=0} = C_\delta$$

and

$$\upsilon = \frac{Q_a}{F},\ \ W_p = \varepsilon W_a,\ \ \varepsilon = 1 - \frac{W_\delta}{W_a}. \quad (3)$$

Here, N_c is the flow of dissolved oxygen that enters the surface of the biofilm through the boundary layer; $K_c a$ is the mass transfer coefficient; $F_{\delta l}$ is the total area of the biofilm surface in the aerotank; Q_a and W_a are the flow and volume of the aerotank; W_p and W_δ, are, respectively, the fluid volume and loading in the volume of the aerotank; C, C_δ, C_a, and C_o are, respectively, the concentrations of oxygen in the biofilm, on the surface of the biofilm, in the aerotank, and in the wastewater at the aerotank entrance; and z is the coordinate that varies depending on the thickness of the biofilm. The explanation of other parameters is given below.

In a general case, the velocities of oxygen use reactions occurring in the biofilm and in the aerotank, taking into account the possible oxygen consumption at the expense of the withdrawal of microbial die-off products, are described by the following equations:

$$R_c = \alpha_1 R_L + \alpha_2 b_c\frac{C}{K_{m_c} + C}X, \quad (4)$$

$$R_L = \frac{\mu_m}{Y}\cdot\frac{L}{K_{m_L} + L}\cdot\frac{C}{K_{m_c} + C}X, \quad (5)$$

$$R_{a_c} = \alpha_{1a}R_a + \alpha_{2a}b_{a_c}\frac{C_a}{K_{m_{ac}} + C_a}X_a \quad (6)$$

and

$$R_a = \frac{\mu_{m_a}}{Y_a}\cdot\frac{L_a}{K_{m_a} + L_a}\cdot\frac{C_a}{K_{m_{ca}} + C_a}X_a. \quad (7)$$

Here, we recall that b_c and b_{ac} are, respectively, the constants of the die-off microorganisms in the biofilm and the active sludge in the aerotank; α_1, α_2, α_{1a}, and α_{2a} are, respectively, the known stoichiometric factors of using oxygen for oxidizing an OP unit and for self-oxidation of microbial die-off products in the biofilm and the active sludge. The denotation of other variables in the above equations is given in [6, 16].

In order to assess the impact of the aforementioned mechanisms of supply and consumption of oxygen for the OP removal, it is advisable to consider the limiting cases of the aerotank operation in the system of biological wastewater treatment:

1. In the absence of a fixed biomass (additional loading), the OP extraction occurs only with the suspended active sludge; for the purpose of supplying and using oxygen, the given equations are solved at N_c=0.

The calculation of the parameters of the oxygen regime in this case, taking into account the specifics of the oxygen supply systems and the aerotank regime, was considered in particular in [7].

2. In the case when the removal of OPs occurs only when the biomass is fixed for loading, i. e., when the action of suspended active sludge is not taken into account, the given equations are solved at R_{ac}=0.

3. In the case when the removal of OPs in the aerotank occurs due to both suspended and fixed biocenoses. It allows for different variants of arranging the loading elements in the volume (in the plan) of the aerotank and for justification of the necessary area $F_{\delta l}$, of the biofilm formed on their surface. The loading elements (nozzles, grids, etc.) can be located throughout the aerotank volume or, more densely and complexly, only on its individual sites.

Depending on the flowchart of arranging the loading elements in the aerotank along its length (in the volume), and therefore, in connection with the accepted reactions in the biofilm and the aerotank, the general equation can be greatly simplified. Then let us consider the possible technological schemes below.

Let us consider the case when the load elements are not sufficiently evenly distributed throughout the length of the aerotank. When equation (2) is solved, we assume with sufficient justification that the removal of OPs in the volume of the aerotank by active sludge occurs by a zero-order reaction, and in the biofilm, it occurs during the first-order reaction [6].

Since in equations (4) and (6), K_m<<C and K_{ma}<<C_a, then for oxygen in the practical calculations, oxidation occurs by the reaction of the zero order in the biofilm and in the aerotank. Thus, for the reactions, the equations are as follows:

$$R_c = \alpha_1 R_L + \alpha_2 b_c X, \quad (8)$$

$$R_L = k_L L = \frac{\mu_m X}{YK_{m_L}}L, \quad (9)$$

$$R_{c_a} = \alpha_{1a}R_a + \alpha_{2a}b_{a_c}X_a \quad (10)$$

and

$$R_a = \frac{\mu_{ma}X_a}{Y_a}. \quad (11)$$

The OP concentration in the biofilm $L(x)$ and, in particular, on the surface L_δ is determined in [17]. The oxygen concentration C in the biofilm and, in particular, on its surface $C\delta$ occurs as a result of solving the equations of concentration C changes in the biofilm. The concentration of oxygen is determined depending on the design of the loading elements on which the biofilm is formed, for example in the form of flat plates with openings or nets of separate cylindrical rods. In this case, with some approximation, the reaction R_{cL} can be assumed to occur according to the dependence

$$R_c = \alpha_1 k_L L_{\delta p} + \alpha_2 b_c X. \quad (12)$$

Thus, in the case of the biofilm formation on a flat surface, the loading dependence for the determination of changes in the concentrations of OPs and oxygen throughout the thickness of the biofilm and, in particular, on its surface is found as a result of solving the following equations:

$$D_L \frac{\partial^2 L}{\partial z^2} - k_L L = 0,\ k_L = \frac{\mu_m X}{Y K_{m_L}} \tag{13}$$

and

$$D_C \frac{\partial^2 C}{\partial z^2} - k_C L_{\delta_p} - \alpha_2 b_c X = 0,\ \ k_C = \alpha_1 k_L \tag{14}$$

under the boundary conditions:

– at z=0,

$$-D_L \frac{\partial L}{\partial z} = K_L \left(L_a - L_\delta\right), \tag{15}$$

$$C_\delta = C_a - \frac{w_c \delta}{K_C}; \tag{16}$$

– at $z=\delta$,

$$\frac{\partial L}{\partial z} = 0,\ \ \frac{\partial C}{\partial z} = 0. \tag{17}$$

Here, $L_{\delta p}$ is the averaged value of the OP concentration in the biofilm; the method of taking it into account when determining the reaction R_c is given in [16].

As a result of solving equation (14) at $k_c L_{\delta p}$=const and $\alpha_2 b_c X$=const to determine the concentration C_δ in the reaction of the zero order, the dependence is the following:

$$C_\delta = C_a - \frac{w_c \delta}{K_C},\ \ w_c = k_C L_{\delta_p} + \alpha_2 b_c X. \tag{18}$$

Thus, taking into account the aforementioned, further implementation of equation (2) should be written in this form:

$$-\upsilon \frac{\partial C_a}{\partial x} + \varepsilon\alpha K_c a\left(\beta C_p - C_a\right) - \frac{F_\delta}{F} w_c \delta - w_{ac} = 0 \tag{19}$$

and

$$w_{ac} = \alpha_{1a} w_a + \alpha_{2a} b_{a_c} X_a,\ \ w_a = \frac{\mu_{ma} X_a}{Y_a}.$$

First, let us write equation (19) is the dimensionless form:

$$\frac{\partial \bar{C}_a}{\partial \bar{x}} + A_n \bar{C}_a + A_p = 0,\ \ \bar{C}_a = \frac{C_a}{C_0},\ \ \bar{x} = \frac{x}{l}. \tag{20}$$

As a result of solving equation (19) for the boundary conditions at the entrance to the aerotank with $\bar{C}_a = 1$ at x=0 (C_a=C_o)), taking into account the dependences w_c and w_{ac} to determine the concentration change throughout the length x of the aerotank within the region $0 \le x \le l$, we observe

$$\bar{C}_a\left(\bar{x}\right) = \left(1 - M\right) e^{-\tilde{x}} - M, \tag{21}$$

where

$$M = \frac{A_p}{A_n},\ \ A_n = \frac{\varepsilon\alpha K_C a l}{\upsilon},\ \ \tilde{x} = A_n \bar{x}$$

and

$$A_p = \frac{F_\delta l w_c \delta}{\upsilon F C_0} + \frac{w_{ac} l}{\upsilon C_0} - \frac{\varepsilon\alpha K_C a \beta C_p l}{\upsilon C_0}. \tag{22}$$

To determine the concentration at the exit from the aerotank C_a(l) by equation (21), it is necessary to assume that $\bar{x} = 1\left(x = l\right)$. Let us recall that here and below F_δ is the area of the surface of the biofilm per unit length of the aerotank (reactor).

It should be noted that calculations are considerably more complicated if, at extracting OP, reactions occur between the active sludge and the biofilm according to the well-known Mono equation. In this case, it is necessary to assume in the above equations the reaction rates R_L and R_a according to Mono; the method of respective calculation is given in [17, 18].

The technological procedure of the plugflow aerotank operation consists of two parts, which we will call reactors 1 and 2. There are two possible cases here (Fig. 1).

In the first case (Fig. 1, *a*), in the first part, there is reactor 1 in which the OP removal occurs due to the fixed biomass that is formed at the site of reactor 1 under the established load. In the second part, there is reactor 2, in which the OP extraction is performed by a suspended biomass (active sludge), i.e., it works as a normal plugflow aerotank. In this case, we use the general equation (2) to determine the concentration of oxygen in reactors 1 and 2. At the same time, since in reactor 1 with the length l_1 the wastewaters with a significant initial concentration of L_f=L_o are directly received, then it would be expedient to assume the OP removal in reactor 1 to be reaction of the zero order, and in reactor 2 with the length l_2 it is reaction of the first order. To ensure oxygen utilization, OPs are extracted in zero-order reactors. Then in this case, in order to determine changes in the concentrations of oxygen along the length of reactors 1 and 2 by formula (21), the values of the parameters M, A_n, and A_p will be taken as follows.

For reactor 1 with the length l_1 and with a fixed biomass (biofilm), i. e., within the site $0 \le x \le l_1$, we have

$$M_1 = \frac{A_{n_1}}{A_{p_1}},\ \ A_{n_1} = \frac{\varepsilon\alpha_1 K_{C_1} a l_1}{\upsilon_1},\ \ \tilde{x}_1 = A_{n_1}\bar{x}_1,$$

$$\bar{x}_1 = \frac{x}{l_1},\ \ A_{p_1} = \frac{F_{\delta_1} l_1 w_{c_1} \delta_1}{\upsilon_1 F_1 C_{0_1}} - \frac{\varepsilon\alpha_1 K_{C_1} a \beta_1 C_{p_1} l_1}{\upsilon_1 C_{0_1}}, \tag{23}$$

$$w_{c_1} = \alpha_{1_1} w_{l_1} + \alpha_{2_1} b_{c_1} X_1$$

and

$$w_{L_1} = \frac{\mu_{m_1} X_1}{Y_1},\ \ F_1 = \frac{Q_{a_1}}{\upsilon_1},\ \ C_{0_1} = C_0.$$

In this case, in order to determine the concentration of oxygen at the exit from reactor 1 (at the entrance to reactor 2) $C_1(l_1)$, it is necessary to assume that $\bar{x}_1 = 1\left(x = l_1\right)$.

For reactor 2 with the length l_2, i. e., within the site $l_1 \le x \le l_1 + l_2$ with suspended biocenosis (active sludge), we have

$$M_2 = \frac{A_{n_2}}{A_{p_2}},\quad A_{n_2} = \frac{\varepsilon\alpha_2 K_{C_2} a l_2}{\upsilon_2},\quad \tilde{x}_2 = A_{n_2}\bar{x}_2.$$

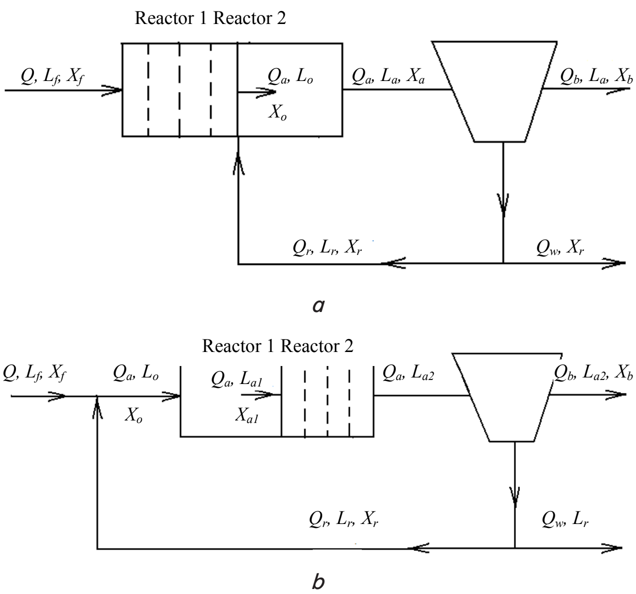

Fig. 1. Flowcharts of biological purification in plugflow aerotanks: *a* – a fixed biomass that is located in reactor 1; *b* – a fixed biomass that is located in reactor 2

$$\bar{x}_2 = \frac{x - l_1}{l_2},\quad A_{p_2} = \frac{l_2 w_{c_2}}{\upsilon_2 C_{0_2}} - \frac{\varepsilon\alpha_2 K_{C_2} a\beta_2 C_{p_2} l_2}{\upsilon_2 C_{0_2}}, \tag{24}$$

$$C_{0_2} = C_{a_1}\ l_1\ ,\quad F_2 = \frac{Q_{a_1}}{\upsilon_2}$$

and

$$w_{c_2} = \alpha_{1_2} k_{a_2} L_{a_2} + \alpha_{2_2} b_{c_2} X_{a_2},\quad k_{a_2} = \frac{\mu_{m_2} X_{a_2}}{Y_{a_2} K_{m_{a_2}}}.$$

To determine the concentration of oxygen at the exit from reactor 2 (at the exit of the aerotank) $C_{0_2}(l)$, it is necessary to assume that $\bar{x}_2 = 1(x = l_1 + l_2 = l)$. In the above equations, C_{0_1} and C_{0_2} are, respectively, the concentrations at the inlets to reactor 1 and reactor 2.

In the second case (Fig. 1, *b*), in reactor 1, the removal of OPs occurs due to the suspended biomass (active sludge), i. e., it operates as a normal plugflow aerotank, and in reactor 2, the OP extraction occurs mainly due to the fixed biomass in the set load. Since it is too difficult and costly to perform extra cleaning in existing traditional aerotanks, such a flowchart of purification would be appropriate from a practical point of view. In addition, such a scheme is more consistent with modern requirements for ensuring a high degree of purification [3].

In this case, we use the general equations (2) to determine the concentration of oxygen in reactors 1 and 2. Since the sewage of a significant initial concentration directly comes to reactor 1 of the length l_1, it would be expedient to consider the OP extraction with active sludge in reactor 1 as the zero-order reaction, and in reactor 2 of the length l_2, where cleaning of the OPs is secured by the biocenosis (biofilm), it will be the first-order reaction. As in the previous case, for the provision of oxygen, the OP utilization is performed in zero-order reactors. Then, in order to determine the change in the concentration of oxygen over the length of reactors 1 and 2 by formula (21), the values of the parameters M, A_n, and A_p will be assumed as follows.

For reactor 1 with the length l_1 within the site $0 \le x \le l_1$, we have

$$M_1 = \frac{A_{n_1}}{A_{p_1}},\quad A_{n_1} = \frac{\varepsilon\alpha_1 K_{C_1} a l_1}{\upsilon_1},\quad \tilde{x}_1 = A_{n_1}\bar{x}_1,$$

$$\bar{x}_1 = \frac{x}{l_1},\quad A_{p_1} = \frac{w_{a_{c_1}} l_1}{\upsilon_1 C_{0_1}} - \frac{\varepsilon\alpha_1 K_{C_1} a\beta_1 C_{p_1} l_1}{\upsilon_1 C_{0_1}}, \tag{25}$$

$$w_{a_{c_1}} = \alpha_{1_1} w_{a_1} + \alpha_{2_1} b_{c_1} X_{a_1}$$

and

$$w_{a_1} = \frac{\mu_{m_{a_1}} X_{a_1}}{Y_{a_1}},\quad F_1 = \frac{Q_{a_1}}{\upsilon_1},\quad C_{0_1} = C_0.$$

To determine the concentration of oxygen at the outlet from reactor 1 (at the entrance to reactor 2) $C_1(l_1)$, it is necessary to assume that $\bar{x}_1 = 1(x = l_1)$.

For reactor 2 of the length l_2, i. e., within the site $l_1 \le x \le l_1 + l_2$, with the fixed biomass (biofilm), we have

$$M_2 = \frac{A_{n_2}}{A_{p_2}},\quad A_{n_2} = \frac{\varepsilon\alpha_2 K_{C_2} a l_2}{\upsilon_2},\quad \tilde{x}_2 = A_{n_2}\bar{x}_2,$$

$$\bar{x}_2 = \frac{x - l_1}{l_2},\quad A_{p_2} = \frac{F_{\delta_2} l_2 w_{c_2} \delta_2}{\upsilon_2 F_2 C_{0_2}} - \frac{\varepsilon\alpha_2 K_{C_2} a\beta_2 C_{p_2} l_2}{\upsilon_2 C_{0_2}}, \tag{26}$$

$$C_{0_2} = C_{a_1}(l_1),\quad F_2 = \frac{Q_{a_2}}{\upsilon_2}$$

and

$$w_{c_2} = \alpha_{1_2} k_{L_2} L_{\delta_{p_2}} + \alpha_{2_2} b_{c_2} X_2,\quad k_{L_2} = \frac{\mu_{m_2} X_2}{Y_2 K_{m_2}}.$$

In the above dependencies (23)–(26), the parameters with index 1 refer to reactor 1, whereas those with index 2 belong to reactor 2.

It should be noted that the OP extraction in reactor 2 occurs only due to the fixed biomass (biofilm). It is possible that a certain extraction of OPs due to the active sludge, which is present in the volume W_2 of reactor 2, will be unchanged and, therefore, not taken into account.

The determined additional effect of removing OPs in reactor 2 due to the active sludge can be taken into account when advantage is taken of the general solution of this problem, namely dependencies (21) and (22). For this, it is necessary to make calculations for the aerotank (reactor 2) of a length $l = l_2$, in which there is a joint OP extraction by means of the suspended and fixed biocenoses.

For the implementation of the proposed models and calculations, let us consider some of the features and prerequisites that have been adopted in the formation of the oxygen regime in the plugflow aerotanks with additional fixed biomasses. Thus, in the equations describing the OP extraction by a fixed biomass during the first-order reaction and in the equations describing the consumption of oxygen by the zero-order reaction, with sufficient justification [5, 7, 19], the averaged value for the thickness of the biofilm L_{δ_p} for the calculation is assumed to be as follows:

$$L_{\delta_p} = 0.5\left(L_{\delta_{z=0}} + L_{\delta_{z=\delta}}\right), \tag{27}$$

where $L_{\delta_{z=0}}$ is the concentration of OPs on the outer surface of the biofilm at $(z=0)$, and $L_{\delta_{z=\delta}}$ is the value of OP concentration on the internal surface of the biofilm at $(z=\delta)$.

To determine the concentrations $L_{\delta_{z=\delta}}$ and $L_{\delta_{z=0}}$, solutions are provided in studies [17, 18] to problems for determining the concentration L change in biofilms.

5. Research findings on biotreatment in plugflow aeration tanks with fixed biomasses

According to the proposed models and calculation methods, the oxygen supply for OP extraction processes is usually reduced to determining the known mass transfer coefficients $K_c a$ and K_{cn} and other related parameters. It should be noted that the flowcharts of supplying oxygen and the peculiarities of its use in aerotanks with active sludge have been investigated sufficiently. However, in plants where the OP extraction occurs directly by a biomass that is fixed on loading elements (biofilm), the oxygen regime has not been studied enough. It has been assumed that the process of OP extracting is not limited in terms of oxygen, i. e., the latter is provided in sufficient quantities and is maintained mainly in a concentration that is close to the saturation value. Incidentally, the processes of supplying oxygen to microorganisms in a fixed biofilm and suspended active sludge flakes are somewhat different. This should be taken into account when calculating the consumption of oxygen in the disposal of contaminants by fixed and suspended biomasses.

These features in calculations of the oxygen regime in reactors with suspended and fixed biomasses, which is mainly reduced to the substantiation of determining the coefficients $K_c a$ and K_{cn}, are considered in our paper [20].

In the future, based on the proposed models and methods of calculation, it is necessary to conduct an analysis and impact assessment in order to ensure the supply of the required amount of oxygen to the place of the reaction and OP utilization.

As a result of studies [18, 21, 22], it was established that under a considerable (saturated) formation of the loading elements in the aerotank (reactor), oxygen in the biofilm can be applied at the pneumatic (bubble) aeration. Moreover, it is supplied not only from the volume of the liquid (dissolved oxygen) but also as a result of the so-called cross-surface transfer (CST) directly from the bubbles that are attached to the biofilms. In this case, the streams of contaminants and dissolved oxygen in the biofilm due to its modified surface will be determined as follows:

$$N_L = (1-\eta)K_L\left(L_a - L\big|_{z=0}\right), \tag{28}$$

$$N_c = (1-\eta)K_C\left(C_a - C\big|_{z=0}\right) + \eta\alpha K_{cn}\left(\beta C_p - C\big|_{z=0}\right) \tag{29}$$

and

$$W_p = \varepsilon W_a, \quad \eta = \frac{F_{\delta_n}}{F_{\delta l}},$$

where F_{δ_n} is the total area of the biofilm surface, for example, in reactor 2, which is in contact with air bubbles, and $F_{\delta l}$ is the total surface area of the biofilm in the aerotank (reactor).

In the preceding case, technological oxygen for the OP utilization was added to the biofilm in the form of dissolved oxygen formed in the liquid due to bubbles. Moreover, according to (29), dissolved oxygen in the biofilm is supplemented with oxygen directly from the bubbles as a result of the CST. Therefore, the equation for the biofilm (14) must be solved under the following boundary conditions at z=0:

$$N_c = P_1 - P_2 C_\delta, \tag{30}$$

where

$$P_1 = (1-\eta)K_c C_a + \eta\alpha K_{cn}\beta C_p,$$

$$P_2 = (1-\eta)K_c + \eta\alpha K_{cn}, \quad w_c = \alpha_1 k_L L_{\delta p} + \alpha_2 b_c X;$$

$$\varepsilon = \frac{W_{p2}}{W_{a2}}$$

and

$$k_L = \frac{\mu_m X}{Y K_{m_L}}.$$

As a result of solving equation (14) with the boundary conditions at z=0 (30) and $z=\delta;\ \dfrac{\partial C}{\partial r}=0,$ we have the following:

$$P_2 C_\delta = P_1 - w_c\delta \tag{31}$$

and

$$C_\delta = \frac{P_1 - w_c\delta}{P_2}. \tag{32}$$

For example, in the case when the removal of OPs in reactor 2 occurs only due to the biomass that is attached to the loading elements, the equation for determining the change in the concentration C_a in reactor 2, taking into account the CST, will have the form

$$-\upsilon_2\frac{\partial C_{a_2}}{\partial x} + \varepsilon\alpha_2 K_{C_2} a\left(\beta_2 C_{p_2} - C_{a_2}\right) - \\ -\frac{F_{\delta_2}}{F_2}(1-\eta_2)K_{C_2}\left(C_{a_2} - C_{\delta_2}\right) = 0 \tag{33}$$

and

$$F_2 = \frac{Q_{a_2}}{\upsilon_2}, \quad \varepsilon = \frac{W_{p_2}}{W_{a_2}}, \quad \eta_2 = \frac{F_{\delta_{n2}}}{F_{\delta_2}}.$$

Here, the concentration C_{δ_2} is determined by formula (32), using the necessary parameters for removing OPs in reactor 2.

Thus, the CST in the aforementioned technological schemes of purification in plugflow aeration tanks can be accomplished by using the concentration value on the surface of the biofilm C_δ in the proposed equations and dependences according to dependence (32).

Substantial research on the effect of the CST has been carried out for purifying water through biofilm models with filtration [18, 22, 23]. It has been established that taking the CST into account can increase the purification parameters by 15–20 %, especially under purification conditions at significant concentrations and significant sizes of bubbles.

In the aerotank (reactor) in Fig. 1, where the removal of OPs occurs due to active sludge, if recirculation has to be taken into account, the expenditure of Q_a will be determined by the known formula:

$$Q_a = Q(1+r), \quad (34)$$

where Q is the estimated wastewater spending, m^3/h (Fig. 1), and r is the degree of recirculation of active sludge, which is taken in accordance with [19].

6. Discussion of the research findings on biotreatment in plugflow aeration tanks with fixed biomasses

The obtained calculated dependencies and the implementation of the proposed models and methods of calculating can help estimate the influence of various purification factors in plugflow aerotanks, in which the purification intensity increases due to additional elements with an attached biocenosis.

These models take into account the parameters of the biofilm, the hydrodynamic peculiarities of the intake of organic contaminants and oxygen in the biofilm, and the velocities of kinetic reactions with the joint removal of organic contaminants by weighed and fixed biocenoses.

As shown by the additional analysis, the proposed mathematical models and calculation methods that are based on their implementation more fully and reasonably consider the important processes that significantly affect OP utilization and, therefore, the efficiency of aerotanks with the additional involvement of purification by a fixed biocenosis.

The scientific and applied values of the results consist in the aforementioned factors as well as in the possibility to use the known equations for calculating the mass transfer of OPs and oxygen in the biofilm and the free volume of aerotanks; the essence is justified by the simplifications in describing the main processes of biochemical purification and in considering the main technological procedures.

The developed models require validation by comparing theoretical and experimental data. This factor can be attributed to disadvantages, but the problem is planned to be solved in further research.

The conducted research is necessary to substantiate the most economical and effective parameters of such structures of biological treatment as aerotanks, which are widely used at stations of clearing household and domestic sewage. This significantly helps improve the quality of removing dissolved organic pollutants from the wastewater and reduce the contaminating load on water objects into which purified wastewater is discharged.

Such studies are a continuation of previous research on the aforementioned topics on the removal of OPs in plugflow aerotanks with additional attached biomasses under the condition of a complete provision of this process with oxygen.

In the future, based on the proposed models and methods of calculation, it is supposed to conduct an analysis and evaluation of the influence of the main factors as well as to identify the parameters of supplying the required amount of oxygen to the place of the reaction and OP utilization.

7. Conclusions

1. The study has presented a mathematical model of the process of removing OPs in plugflow aerotanks, based on equations of transferring OPs and oxygen in the free volume of aerotanks and in biofilms as well as on dependencies describing oxygen consumption and OP oxidation. The mechanisms of the aerobic purification process and the features of the simultaneous removal of organic contaminants by biofilms and suspended biocenosis are taken into account.

2. A number of assumptions have been adopted to simplify the mathematical model and to obtain analytical dependencies for the possibility to develop engineering calculations. The transfer equations disregard the diffusion component. It is assumed that the process of OP oxidation by suspended active sludge occurs in a zero-order reaction, and in a biofilm, it occurs by a first-order reaction.

3. The calculated dependencies have been obtained for various flowcharts of arranging a reactor with an attached biomass. They represent the dependence of the OP concentration at the output of the plugflow aeration tank, which contains elements with the attached biocenosis, on the reactor parameters: length, surface area of additional elements, velocity of sewage, etc.

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