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# Theoretical studies and calculations of wastewater treatment in trickling biofilters

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**Summary.** On the basis of the analysis of existing models and methods of calculation, proposed a general mathematical model of the process of removal of organic contaminants in an aerobic biological wastewater treatment in trickling biofilters with sufficient support biooxidation by oxygen. Results of comparison of theoretical calculations with experimental data obtained by different authors in trickling biofilters with different loading are presented. As the results, the theoretical calculations are in general well correlated with the experimental data.

**Key words:** biofilter, waste water, biological film, model, treatment

## INTRODUCTION

An important aspect of environmental problems is to develop a reliable, efficient and economic facilities for treatment of domestic wastewater. In accordance with regulatory requirements it is necessary to conduct a more advanced biological wastewater treatment. Recently becoming more common in practice the biological reactors of different designs, due to the formation of high concentration of microorganisms in the form of attached biofilm on the material loading of the bioreactor, which is effective in removing organic and other contaminants [1, 2, 3, 4, 5].

Biological wastewater treatment in structures with attached biomass in the form of biofilms has some significant advantages and is widely used in practice and the research of biofilm wastewater treatment processes was developed quite extensively. Unlike flooded filters, in trickling biofilters effluent liquid flows down as a layer over the surface of the feed material that can be run in the form of plates made of polymeric materials or of particles of different rocks [1, 2, 6, 7]. In addition, the air enters the natural way at the top or bottom of the filter with flat flow.

Existing researches on the basis of which was developed and proposed the methods of calculation have been mostly empirical in nature and were developed using simplified approaches (models) and simple theoretical approaches (models). So as a result of the analysis of existing models and methods of calculation of treatment parameters of trickling filters [3], and taking into account also the shortcomings of existing research in [8] the most comprehensive and advanced three-phase mathematical model consists of hydrodynamic block and dynamics block of organic contaminants and air (oxygen) in trickling filters was formulated and proposed. The general scheme of this model is presented in [8, 9]. The mathematical model is described by a system of interrelated equations the solution of which determines the changes in the concentration of contaminants and oxygen in layers and in a trickling filter as a whole. The analysis of the mathematical model showed that for use in practical calculations, the general model can be simplified, namely considering the flow of contaminants in the biofilm and their removal at a constant conditions. This takes into account that the aerobic treatment process in sufficient quantity provided with oxygen, that is not limited by oxygen, as well as a number of other conditions, which are generally valid and do not introduce significant errors in the calculations [1, 4, 5].

On the basis of implementing the model the engineering methods of calculation of technological and design parameters of treatment trickling filters were proposed [10, 11]. Dependences for determining the variation of contaminant concentration on the thickness of the biofilm and the height of the biofilter under different possible speeds (kinetic) reactions remove organic contaminants are proposed too. The criteria and recommendations to determine the feasibility and optimal thickness of the active biofilms, within which there is an almost complete purification from entering contaminents take place are presented. In [11] to perform the calculations the necessary recommendations on the choice of parameters and coefficients that appear in equations and dependencies are given. The overall biofilm is a heterogeneous structure and the study of the processes occurring in the biofilm devoted a lot of work [4, 5, 12, 13, 14]. So an important parameter in the calculation is determining the calculated thickness of the biofilm, which in this case is an active thickness, consisting of heterotrophic microorganisms, and the formation of its basic parameters largely depends on the load and hydraulic conditions in the biofilter with attached biocenosis. In works [1, 11] on the basis of the implementation of the general equations for determining the formation of the thickness of the biofilm are given specific dependencies to determine it active part taking into account the processes increasing the biofilm thickness, the disintegration of the biofilm and the speed of detachment from its surface. Moreover, we note that in biofilters with attached biocenosis thickness of the biofilm filter will decrease due to the decrease in the concentration of contaminants that are extracted, and with the increase in the specific surface of the material load. The proposed models and methods in general allow us to consider this fact.

A comparative analysis of theoretical calculations with experimental data, which indicates that the proposed model and developed on the this basis the methods of computation for adopted the averaged constant values of thickness of the biofilm $\delta$ sufficiently reliable and adequately describe and show the processes in these cases [1, 4, 13, 14, 15].

## JUSTIFICATION OF THE MODEL AND METHOD OF CALCULATION

In this article we discussed the basic positions and the results of theoretical studies of aerobic biological wastewater treatment of organic contaminants in trickling biofilters. So, to determine changes in the concentration of organic contaminants (OC) $L$ within the biofilm thickness $\delta$ (Fig. 1) it is necessary to obtain the solution of the following equation:

$$D_L \frac{\partial^2 L}{\partial x^2} - R_L = 0, \qquad (1)$$

which is performed under the following boundary conditions:

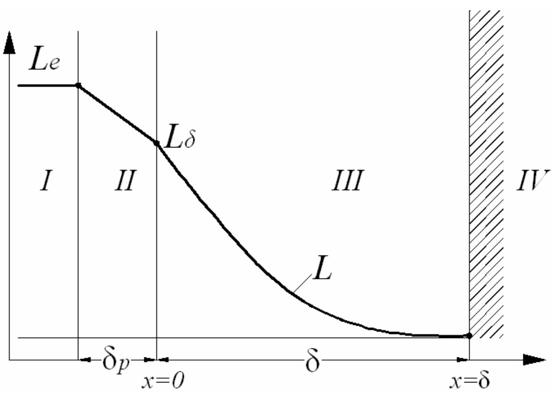

**Fig. 1.** Concentration profiles $L$ in the biofilm and the liquid film: *I* – fluid flow, *II* – liquid film, *III* – biofilm, *IV* – element load

$$N = -D_L \frac{\partial L}{\partial x} = K_L \left( L_e - L\big|_{x=0} \right) \quad \text{when} \quad x = 0$$

$$\frac{\partial L}{\partial x} = 0 \qquad \text{when} \quad x = \delta . \qquad (2)$$

It is known [1, 8] that if the process of waste recovery is not limited by the oxygen that is provided by the oxygen in sufficient quantity and the reaction rate in the absence inhibitory effect is expressed by the known equation of Monod:

$$R_L = \frac{\rho_m L}{K_m + L}, \quad \rho_m = \frac{\mu_m X}{Y}. \qquad (3)$$

Considering that at comparing low concentrations of contaminants often can be taken $K_m >> L$, and at significant concentrations $K_m << L$ and in these cases the reaction kinetics can be respectively the first and zero order terms, namely:

$$R_{L1} = kL, \qquad k = \frac{\rho_m}{K_m}; \qquad (4)$$

$$R_{L0} = w_L, \qquad w_L = \frac{\mu_m}{Y} X, \qquad (5)$$

In the above equations and dependencies the following notation of some of the parameters and coefficients are given:

$L$, $L_e$, $L_0$ – the concentration of organic contaminants in the biofilm in the filter and in the input liquid respectively, BOD(g/m$^3$), COD(g/m$^3$),

$\delta$, $\delta_p$ – the calculated thickness active (aerobic) biofilm and liquid film (boundary layer) respectively, *m*,

*D* – the coefficient of molecular diffusion in the biofilm, m$^2$/h,

$K_L$ – the coefficient of mass transfer of organic contaminants in the liquid film, m/h;

$K_m$ – the saturation constant (halfsaturation) for organic pollutants, BOD(g/m$^3$), COD(g/m$^3$),

$\mu_m$ – maximum specific growth rate of microorganisms, $h^{-1}$,

$Y = \frac{dX}{dL}$ – the stoichiometric coefficient of the biomass, g/g,

*X* – the concentration of biomass in the biofilm, BOD(g/m$^3$), COD(g/m$^3$).

As a result of solving equation (1) with boundary conditions (2) for first order reactions $R_{L1}$ (4) we get the following relationship for the changes concentration *L* on the thickness of the biofilm $x$:

$$L(\bar{x}) = L_e \frac{e^{\sqrt{\alpha}(2-\bar{x})} + e^{\sqrt{\alpha}\cdot\bar{x}}}{\left(e^{2\sqrt{\alpha}} + 1\right) + \lambda\left(e^{2\sqrt{\alpha}} - 1\right)}, \qquad (6)$$

$$\text{where} \quad \alpha = \frac{k\delta^2}{D_L}, \quad \lambda = \frac{\sqrt{kD_L}}{K_L}, \quad \bar{x} = \frac{x}{\delta}.$$

Dependence to determine the concentration of contaminants on the outer surface of the biofilm will get from equation (6) when the value $\bar{x} = 0$:

$$L(0) = L_\delta = AL_e, \qquad (7)$$

$$\text{where } A = \frac{1 + e^{-\varphi}}{\left(1 + e^{-\varphi}\right) + \lambda\left(1 - e^{-\varphi}\right)}, \varphi = 2\sqrt{\alpha}. (8)$$

On the basis of the dependence (8) for determining the parameter *A* built design chart $A = f(\varphi, \lambda)$ (Fig. 2). Using the dependence (7) equation (6) can be simplified to this:

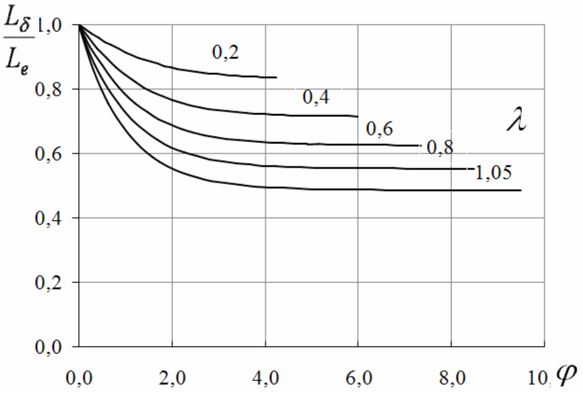

**Fig. 2.** A graph of the dependence $A = f(\varphi, \lambda)$. Graph for determining the parameter *A* for prismatic download: *1* – δ = 0,0001 m, *2* – δ = 0,0002 m, *3* – δ = 0,0003 m

$$L(\bar{x}) = \frac{\operatorname{ch}\sqrt{\alpha}(1-\bar{x})}{\operatorname{ch}\sqrt{\alpha}} L_\delta \text{ , where } \sqrt{\alpha} = \frac{\varphi}{2}. \quad (9)$$

Solving equation (9), we can estimate the efficiency of treatment in this case by establishing a full or partial penetration of OC in the biofilm.

The solution of equation (1) for a zero order reaction $R_L$ (5) considers the following two cases with different boundary conditions. In the first case, which corresponds to the complete penetration of organic contaminants in the biofilm ($\beta \geq 1$), the solution of equation (1) is performed with the boundary conditions (2), as a result, will receive the following relationship to determine the concentration $L$ in the biofilm:

$$L(x) = L_e - \frac{w_L}{D_L}\left(\frac{\delta D_L}{K_L} + \delta x - \frac{x^2}{2}\right). \quad (10)$$

The value of concentration at the biofilm surface ($x=0$) will be:

$$L_\delta = L_e - \frac{w_L \delta}{K_L} \ . \quad (11)$$

With (11) equation (10) may be write for father analysis in the form:

$$L(x) = L_\delta\left[1 - \left(\frac{2x}{\delta\beta^2} - \frac{x^2}{\delta^2\beta^2}\right)\right] , \quad (12)$$

$$\beta = \sqrt{\frac{2L_\delta D_L}{w_L \delta^2}} \text{ or } \beta\delta = \sqrt{\frac{2L_\delta D_L}{w_L}} \ . \quad (13)$$

In the second case, which corresponds to the partial penetration of organic contaminants in the biofilm ($\beta < 1$) the solution of equation (1) is provided at $L=0$ on the border $x = \delta$ instead of $\frac{\partial L}{\partial \mathrm{x}} = 0$ in the previous case:

$$L(x) = L_\delta\left(1 - \frac{2x}{\beta\delta} - \frac{x^2}{(\beta\delta)^2}\right), \quad (14)$$

$$L_\delta = \frac{L_e - \frac{w_L \delta}{K_L}}{\left(1 - \frac{D_L}{\delta K_L}\right)}. \quad (15)$$

If in many cases the ratio $\frac{D_L}{\delta K_L}$<<1 then in both cases of the value $\beta$ we can use the dependence (11) that to determine the concentration $L_\delta$.

To determine fluxes using equation (2) in [11] lists the order of calculation first order kinetics and zero order at the condition of partial and full penetration of organic contaminants in the biofilm. Also, the graph of the concentration profiles for the kinetics order zero in the middle of the biofilm at different values of $\beta$<1 and $\beta$>1 was provided. Profiles constructed with a constant thickness of the biofilm $\delta$ and correspond each to a specific value of the concentration $L_e$ which changes along the height of the filter.

The above solutions are obtained for the kinetics of reactions $R_L$ of the first and zero orders of magnitude, which corresponds to low and high concentrations of organic contaminants. According to [15], in practical calculations this corresponds to the relations $\beta_L = \frac{K_m}{L_0}$>2 and $\beta_L$<0,25. In addition in wastewater treatment by biofilters in some cases we get the ratio $\beta_L$ within the boundaries of 0,25 < $\beta_L$ < 2. In these cases, the calculations of the reaction kinetics $R_L$ take the known Monod equation (3). In [15] to determine the concentration of $L$ in the biofilm, namely on the surface $L_\delta$, a method for solving equation (1) at given kinetic response of $R_L$, according to equation Monod was proposed. The nature and sequence of the proposed iterative method of calculation are given in [11, 13, 15].

In [11] provides guidance for determining flows OC in the case of the reaction kinetics according to the equation Monod.

According to [8] for determining the change in concentration $L_e$ on height of biofilter is used the equation of conservation of mass of contaminants in the fluid flow of the biofilter in the form of:

$$n_e \frac{\partial L_e}{\partial t} = -Q\frac{\partial L_e}{\partial z} - F_\delta K_L \left(L_e - L_\delta\right). \quad (16)$$

In stationary conditions, which occurs very quickly, in a result of solving equations (16) at $n_e \frac{\partial L_e}{\partial t} = 0$ and when taking into account the dependence (7) for $L_\delta$ and boundary conditions $L_e = L_0$ at $z=0$ for practical calculations for the reaction of the first order we obtain a following dependency:

$$\overline{L}_e = e^{-B\overline{z}} \approx e^{-\tilde{z}}, A_* = K_L F_\delta \left(1 - A\right), \quad (17)$$

Here: $\overline{L}_e = \frac{L_e}{L_0}$, $\overline{z} = \frac{z}{S}$, $B = \frac{A_* S}{Q}$,

$$\tilde{z} = B\overline{z} = \frac{A_*}{Q} z .$$

To determine the concentration at the outlet of the filter (in filtrate) $z = S$, we obtain:

$$L_{eS} = L_0 e^{-\tilde{S}}, \qquad B = \tilde{S} = \frac{A_*}{Q} S , \quad (18)$$

and to determine the working height of the filter S at a known predetermined parameters $L_0$, $Q$, $\varepsilon$, $L_{eS}$, and $A_*$ we obtain:

$$S = \frac{Q}{A_*} \ln \frac{L_0}{L_{eS}} . \quad (19)$$

In following dependencies:

$F_\delta$ – the surface area of biofilm per unit height of the filter, m,
$S$ – the working height of the filter, m,
$Q$ – flow rate (volumetric flow rate), m$^3$/h.

On the basis of dependence (17) in Fig. 3, 4 built estimated graphs

$$\overline{L}_e = \frac{L_e}{L_0} = f\left(\overline{Q}, \overline{z}\right) \text{ and } \overline{L}_e = \frac{L_e}{L_0} = f\left(\tilde{z}\right),$$

where: $\overline{Q} = \frac{1}{B} = \frac{Q}{A_* S}$.

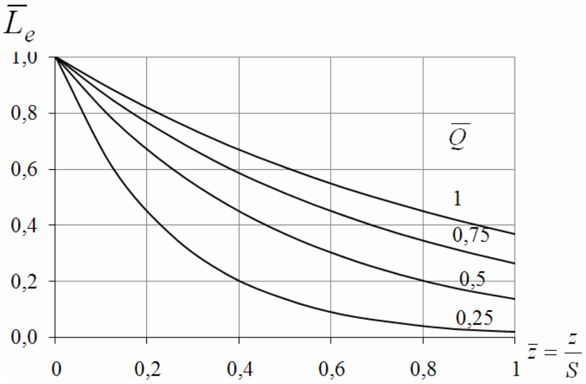

**Fig. 3.** Graph of dependency $\overline{L}_e = \frac{L_e}{L_0} = f\left(\overline{Q}, \overline{z}\right)$

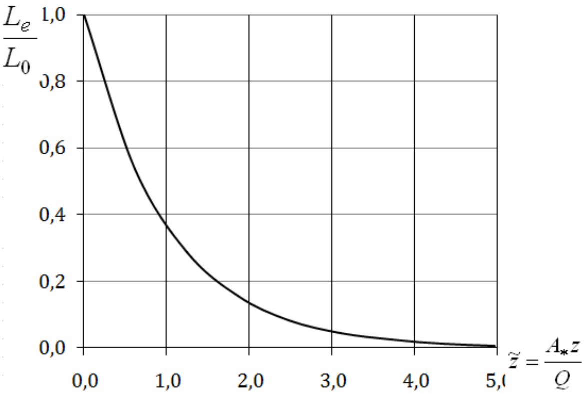

**Fig. 4.** Graph of dependency $\overline{L}_e = \frac{L_e}{L_0} = f\left(\tilde{z}\right)$

As a result of solving equation (16) for the zero order reaction (5) with relation (11) for determining the change in concentration $L_e$ along the height of the filter $z$ we may receive a dependency:

$$L_e = L_0 - \frac{F_\delta}{Q} w_L \, \delta \, z . \quad (20)$$

The concentration at the outlet of the filter ($z$=$S$) will be:

$$L_e(S) = L_0 - \frac{F_\delta}{Q} w_L \, \delta S \,, \qquad (21)$$

and to determine the height of the filter at a predetermined concentration $L_e(S)$ we obtaine following equation:

$$S = \frac{Q}{F_\delta w_L \, \delta} \left( L_0 - L_e(S) \right). \qquad (22)$$

## DISCUSSION OBTAINED RESULTS

Below some of the results of verification and comparative analysis of the proposed models and methods of calculation using existing experimental studies are presented.

Quite reasonable laboratory study on extraction of organic contaminants in sewage treatment biofilter under conditions sufficient supporting of aerobic process by oxygen was carried out in [17]. The reactor (biofilter) was built with PVC 2m high and with a diameter of 0,2 m. Domestic waste water was supplied from below to the central part of the column, air is fed through the holes in the base of the column. As download the elements of waste of polypropylene were used with a diameter of 2,3…2,7 mm, a length of 4…6 mm, the porosity was 0,42.

Concentrations of dissolved oxygen varied from 5.2 to 8.6 mg/l. The researches have shown that these oscillations are not a limiting factor. The researches were carried out for different input concentrations of COD, which varied between $L_0$ = 80…200 mg/l (0,08…0,2) kg/m$^3$. In more detail the methods of researches and their processing are described in [17].

For comparative analysis of the results of theoretical calculations with experimental data has been used the above method of calculation. According to this technique with using given and accepted in the literature source of data the determination of the intermediate parameters ($A$, $A_*$) was conducted and then on the proposed dependencies were defined changes in the concentration on the height of the biofilter based on valid reaction rates in the biofilm for this case. In Fig. 5 shows a comparative graph when the input concentration

$L_0$ = 0,160 kg COD/m$^3$. Additionally note that when performing calculations to construct the theoretical curve $L_e = f(z)$ in particular according to [18], the flow rate value was taken $Q$ = 0,024 m$^3$/h and the specific surface of the feed material $F_{\delta n}$ = 1160 m$^2$/m$^3$, and due to the relatively large surface area $F_{\delta n}$, according to [14], the thickness of the biofilm adopted δ = 25…30 microns. Other necessary input data are accepted on the basis of the guidelines described in the known literature. Thus according to [17] the concentration $L_{en}$ was measured in units of COD and BOD, and the BOD/COD relation was taken of 0,45 for the incoming stream and 0,20 for the effluent (filtrate). On the chart Fig. 5 calculated concentrations are slightly below the experimental one, but there has generally been a good enough match between them.

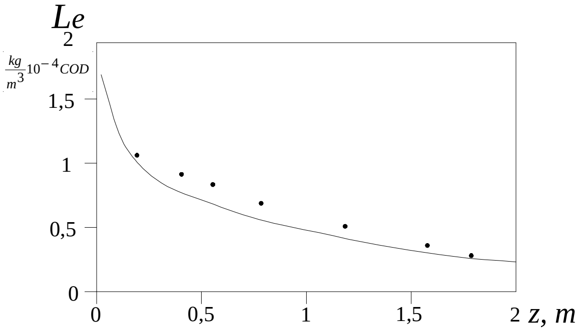

**Fig. 5.** Chart of changes in concentration along the height of the filter $L_e = f(z)$.

To assess the dependencies (18) the experimental data was used that given in [18] that allow us to conduct a comparative assessment of theoretical calculations with experimental data. The calculations were performed using dependencies:

$$\overline{L}_e = \frac{L_e}{L_0} = e^{-B\overline{z}} = e^{-\tilde{z}} \,,$$

$$B = \frac{A_* S}{Q}, \qquad A_* = K_L F_{\delta S} (1 - A),$$

$$F_{\delta S} = F_\delta \cdot S, \qquad \bar{z} = \frac{z}{S}, \qquad (23)$$

which in the determination of the concentration at the outlet of the biofilter (filtrate) take the form:

$$L_{eS} = L_0 e^{-B} = L_0 e^{-\tilde{S}}, \quad B = \tilde{S} = \frac{A_* S}{Q}, \quad (24)$$

here $L_0$ is the input concentration of organic contamination, mg/l;
$S$ – working height of the filter, m;
$F_\delta$ is the surface area of the feed material per unit height of the filter, m;
$K_L$ – coefficient of transfer in the liquid film, m/h;
$A$ – the parameter which is determined according to [10].
For the calculation of the parameter $B$ were taken out the data used in [18] and data taken from the literature. Though the some divergence presents of the experimental data with the calculated, especially for large values $\overline{L}_{eS}$, in general, it can be considered a good coincidence of the experimental data with the calculated.

The results of the comparative evaluation is shown in Fig. 6. It shows that although for large values $\overline{L}_{eS}$ there is some divergence of the experimental data with the calculated, but in general we may count on their good coincidence.

In the literature, in particular [2, 5, 19], on the basis of analysis of existing research results suggested a number of empirical dependences for calculation of parameters of wastewater treatment by biofilters. The basis of this research is a known functional dependence of the concentration of the waste water outlet $L_{es}$ (BOD$_5$) in depending of a number of factors, which with some modifications depend of the type of load and other factors used by different specialists for treatment [21, 22, 23].

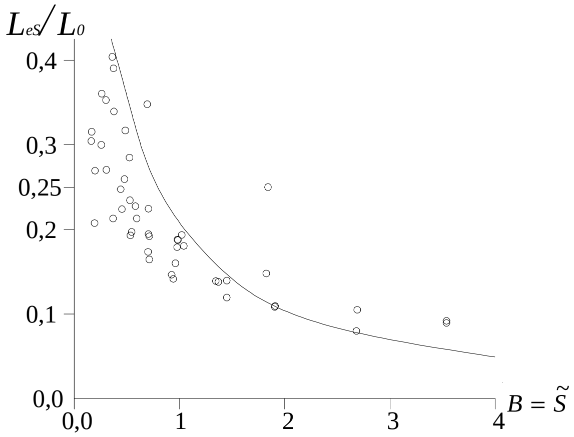

**Fig. 6.** The dependence $L_{es}$ on the parameter $B$ for the gravel biofilter loading, which oxidize urban wastewater:

○ – experimental data, — – estimated curve

Some additions to the calculations.

1. When considering equation (16) the performance of suspended biocenosis in sewage is not taken into account due to its insignificance effect.

2. In accordance with the adopted general model [18], OC receipts from the waste liquid in the biofilm through the liquid film (boundary layer) which is formed on the surface of the biofilm. The analysis showed that it is necessary to consider the OC mass transfer through the boundary layer that implemented in the model in the equation (2) for the flux $N$ as the boundary conditions on the surface of the biofilm. In [11] there are presented and considered recommendations for the implementation of this equation when solving specific problems.

3. When removing contaminants by attached biocenosis (biofilm) on the biofilters of different designs their concentration along the height of the filter will decrease and according to accepted models will lead to the overall reduction in the thickness of the biofilm on the height of the filter. The proposed model and calculation methods allow to consider this fact in principle. In addition, a numerical comparative analysis of theoretical calculations with experimental data that was carried out shows that the proposed model and methods for calculating, based on the

average weighted constant values of thickness δ is sufficiently reliable and adequately describe and show the process of treatment in these cases [1, 4, 13, 15, 23].

4. Extraction of organic contaminants in the biofilm under aerobic conditions is controlled by the flow of oxygen in the biofilm. Organic matter may be present throughout the thickness of the biofilms, but cannot be extracted on the section where oxygen is absent. In biofilters with attached biocenosis (biofilm) at the aerobic process of recycling of organic contaminants it is necessary to provide a dissolved oxygen concentration of at least $C$ > 5 mg/l throught the all active thickness of the biofilm [1, 4, 11, 16]. The speed (limiting) of process will be determined by that substrate that penetrates into biofilm at a shallower depth.

## CONCLUSIONS

1. Implementation of the proposed model with appropriate boundary conditions allows to determine the changes in the concentration of contaminants in the biofilm $L(x)$ and in the filter $L_e(z)$.

2. It helps more securely and reliably to justify the technological and constructive parameters of biofilters that confirms the evaluation testes in laboratory and industrial conditions.

3. The comparative results and their analysis suggests that the proposed model and developed on the basis of their calculation methods to describe and show the process of wastewater treatment in trickling biofilters with sufficient adequacy in general.

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## ТЕОРЕТИЧЕСКИЕ ИССЛЕДОВАНИЯ И РАСЧЕТЫ ОЧИСТКИ СТОЧНЫХ ВОД НА КАПЕЛЬНЫХ БИОФИЛЬТРАХ

**Аннотация**. На основе проведенного анализа существующих моделей и методов расчета, предложена общая математическая модель процесса удаления органических загрязнений при аэробной биологической очистке сточных вод на капельных биофильтрах при достаточном обеспечении биоокисления кислородом. Приведены результаты сравнения предложенных теоретических расчетов с экспериментальными данными полученные разными авторами на капельных биофильтрах с разной загрузкой. Как показывают результаты, теоретические расчеты в целом хорошо сопоставляются с экспериментальными данными.

**Ключевые слова**: биофильтр, сточные воды, биологическая пленка, модель, очистка.