Research of waste water biological treatment in filter grain loads

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Abstract. The biochemical processes occurring in sand filters loads of tertiary treatment of urban wastewater are investigated. The significance of those processes in reducing the overall biochemical and chemical oxygen demand in water purified by filters was established. The studies were conducted in natural conditions of the wastewater treatment plant in Krasnoyarsk using the installation for filters’ technological modeling. Equations for calculating and adjusting filtering parameters, taking into account biochemical processes, were obtained.

1. Introduction

Currently, the shortage of fresh water is becoming a very significant factor in world politics and ensuring international security. The problem of fresh water can become a subject of global political and economic competition.

The basic principles of the State Policy of Russia in the field of water bodies’ use and their protection are enshrined in the Water Strategy of the Russian Federation up to 2020. One of the key areas is guaranteed provision of water resources to the population and sectors of the economy [1].

An important reserve for replenishment of open and underground natural reserves of water supply is the reuse of treated sewage city water in case of their insufficiency in conditions of water shortage. The most commonly used wastewater treatment (tertiary treatment) facilities are quick sand filters.

However, no studies have been conducted to evaluate the significance of biochemical oxidation processes in reducing the overall biochemical and chemical oxygen demand for purified water, and there are no dependencies for their calculation according to the technological parameters of the filtering.

The purpose of these studies is to study the biological treatment processes in granular sand filter loads.

2. Material and methods

Experimental studies of the biological oxidation processes of organic substances in a granular filter load were carried out at the wastewater treatment plant in the city of Krasnoyarsk [2]. The filter model was a filter column with a cross section of 200x200 mm loaded with filtering material from pink sand of a homogeneous composition with a grain size of 1.4 mm. The total loading height was 1350 mm.
The filter was equipped with fittings for the height of the load for water sampling and pressure measurement. During filtration cycles water quality was analyzed for suspended solids, biochemical oxygen demand (BOD5), total and caused by dissolved organics (in the filtered sample), chemical oxygen demand (COD), and dissolved oxygen in water. At the end of the filter cycles, hydrobiological analysis, microscopy of the sludge in the wash water, and determination of its dehydrogenase activity were carried out. Studies have shown that biochemical oxidation processes occur in the filter load. The average results of the experimental 13-hour filter cycles are presented in graphs in Figure 1.

**Figure 1.** Change in filter contamination and quality purified water by depth loading during the filter cycle (1 - after 1 hour; 2 - after 5 hours; 3 - after 9 hours; 4 - after 13 hours).

The filtration rate was 20 m/h, the water temperature was 20 °C. When the quality of the filtered water deteriorated more than 10 mg / l in terms of suspended solids the filter cycles ended.

The general dependences for the biological oxidation process, which reflect the kinetics of the decrease in the biochemical oxygen demand (BOD) and dissolved oxygen in purified water, were adopted according to the Mono model [3-5]. The saturation density of the load changes with sediment over the depth of the load during the filter cycle and filtering, therefore, the model is created for the filter to:

\[
\frac{dL}{dt} = -\frac{\mu_m(T)\rho(T)L}{Y(K_L + L)},
\]

\[
\frac{dO_2}{dt} = -\alpha\frac{\mu_m(T)\rho(T)L}{Y(K_L + L)},
\]

where \(L\) – BOD of purified water, mg / l;
\(t\) – length of time the water is in the load, hour;
\(\mu_m(T)\) - maximum specific oxidation rate, hour \(^{-1}\);
\(T\) – filtering time, hour;
\(\rho(T)\) – saturation density of the sediment charge, depending on the filtration duration, mg / l;
\(Y\) – coefficient of protein transformations in biomass;
\(K_L\) – half-saturation constant, mg / l;
\(O_2\) – oxygen content in the treated water.
\( \alpha_{O_2} \) – specific oxygen consumption coefficient.

For a fixed point in time, equation (1) has a solution [6,7]

\[
t = \frac{Y(L_0 - L_t)}{\alpha \mu_m(T) \rho(T)} + \frac{Y K_L ln(L_0/L_t)}{\alpha \mu_m(T) \rho(T)},
\]

(3)

where \( L_0 \) and \( L_t \) – BOD initial and current time t, mg/l.

At low initial concentrations \( L_0 \), the first term of equation (3) can be neglected [3] according to the oxidation theory. The specific rate of wastewater treatment by BOD due to dissolved organic matter, sludge in the charge is equal to

\[
k_L(T) = \frac{\alpha \mu_m(T)}{Y K_L} = \frac{ln(L_0/L_t)}{\rho(T)t},
\]

(4)

where \( \mu_m(T) \) - organic oxidation rate by ashless sludge substance, hours \(^{-1}\); \( \alpha \) – coefficient taking into account the ash content of sludge.

Similarly, the specific rate of decrease in dissolved oxygen in water, taking into account the proportionality coefficient \( \alpha_{O_2} \), is equal to

\[
k_{O_2}(T) = \frac{\alpha_{O_2} \alpha \mu_m(T)}{Y K_L} = \frac{ln(O_{20}/O_{2t})}{\rho(T)t},
\]

(5)

where \( O_{20} \) and \( O_{2t} \) – initial oxygen content in a current time t.

3. Results

The calculation results of specific oxidation rates and a decrease dissolved oxygen in the load as a whole and in its individual layers are presented by graphs in Figure 2 a.

Approximating dependencies for \( k_L(T; 20^\circ) \) and \( k_{O_2}(T; 20^\circ) \), 1/(g \( \cdot \) hour) in loading

\[
k_L(T; 20^\circ) = k_L(1; 20^\circ) T^{-a_1} = 10.6 T^{-1},
\]

(6)

\[
k_{O_2}(T; 20^\circ) = k_{O_2}(1; 20^\circ) T^{-a_2} = 4.6 T^{-0.3},
\]

(7)

where \( T \) – filtering time, hour.;

\( 20^\circ \) - experimental water temperature, \(^\circ\)C.
Figure 2. Change in the cleaning process speed during the filter cycle.

Where: 1 – in the first layer; 2 – in the second; 3 – in the third; 4 – in the loading as a whole; a – is a change in the specific rates of processes to reduce the total BOD₅, BOD₅ dissolved organics, COD, dissolved oxygen; b – change in the rate constants of reducing the total BOD₅ processes, BOD₅ dissolved organics, COD, dissolved oxygen.

At temperatures higher than 20°C, specific rates of oxidation and decrease in dissolved oxygen can be determined using the Stritter equation [3]

\[
k_{L}(T; t^*)_d = k_{L}(1; 20^\circ C) \cdot 1.047^{t^* - 20^\circ C},
\]

\[
k_{O2}(T; t^*) = k_{O2}(1; 20^\circ C) \cdot 1.047^{t^* - 20^\circ C},
\]

The equation for BOD reduction, determined by the dissolved organics of formula (4) has the form

\[
L_{t,d} = L_{o} e^{-k_{L}(T; t^*)_{d} \rho (T)} t,
\]

where \(t\) – water residence time in loading, hour.

The equation for the dissolved oxygen reduction in the passing through the load treated water

\[
O_{2,t} = O_{2,o} e^{-k_{O2}(T; t^*)_{d} \rho (T)} t,
\]

The dimensionless specific oxygen consumption coefficient \(\alpha^O_2\) in formula (2) according to the results of the experiment is
It is seen from the obtained dependence that the specific oxygen consumption coefficient varies during the filter cycle

\[ \alpha^{O_2}(T=1) = 0.43; \quad \alpha^{O_2}(T=4) = 1.25; \quad \alpha^{O_2}(T=13) = 2.60 \],

It is known that BOD decrease is determined by sorption and biological processes in the loading body due to dissolved organic substances. Oxygen is consumed for the oxidation of organics and endogenous respiration of sludge. From the analysis of obtained values of the quantities \( k_{ld} \), \( k_{O2} \), \( \alpha^{O_2} \), it can be assumed that at the beginning of the filter cycle, BOD decrease is determined by both sorption and biochemical processes. Biochemical processes prevail in the load with accumulation of sludge mass in the process of filtering. The total oxygen consumption increases with a change in the saturation density of the sediment charge. Moreover, most of it is spent on endogenous respiration. Anaerobic zones can appear in the filter body at sufficiently long filter cycles because the oxygen content in the source water is limited.

The final total BOD of the purified water, which is determined by the content of suspended and dissolved organic substances and equal to

\[ L_{t \text{tot}} = L_{t d} + \beta S \], \hspace{3cm} (13)

where \( S_{t} \) - suspended solids in water, mg / l;
\( \beta \) - specific BOD 1 mg of activated sludge, depending on its properties.

During the filter cycle, \( \beta \) value varied from 0.35 to 0.95, depending on the loading layer depth and the filtering duration.

The increase in \( \beta \) loading depth occurred due to the classification of silt particles in the filter body by properties, the retention of larger mineralized particles in the first loading layers along the fluid course, and smaller ones in the subsequent ones.

The well-known formula for calculating biooxidants [6,7]

\[ \lg \left( \frac{L_0}{L_t} \right) = K_{1} t \], \hspace{3cm} (14)

where \( K_{1} \) – oxidation rate constant;
\( t \) – duration of storage water in the biooxidant, hours and the obtained formula

\[ k_{L}(T; t^{*})_{d} = \frac{\ln \left( \frac{L_0}{L_t} \right)}{\rho(T) t} \], \hspace{3cm} (15)

\[ K_{L}(t^{*}) = 0.43 k_{L}(T; t^{*})_{d} \rho(T) \]. \hspace{3cm} (16)

The calculated values of \( K_{tot} \) constant varied from 0.03 to 0.47 days\(^{-1}\), decreasing along the loading depth and during the filter cycle in accordance with the change in the saturation density of loading by sediment. \( K_{1} \) ranged from 0.05 to 0.11 day\(^{-1}\), which is typical for biological treatment processes with a low content of organic substances [8].

The oxidation rate constants were determined both by the total content of organic substances - \( K_{tot} \), and by dissolved organic substances - \( K_{1} \). The calculation results are presented by graphs in Figure 2

4. Discussion

The decrease in \( K_{1} \) constant with respect to the loading depth is apparently due to the fact that water containing more and more difficultly oxidized organic substances enters each subsequent layer. A similar pattern is observed for the oxygen consumption rate constant \( K_{O_2} \).

The degree of difficulty oxidized organics retention was estimated by the value of bichromate oxidizability (COD) as a more universal parameter as a result of its adsorption on activated sludge and
biological decomposition [9]. The kinetics of COD reduction in biologically treated wastewater at low values can be described by a differential equation similar to (1), so [9].

\[
\frac{dC}{dt} = - k_c(T) C \rho(T), \tag{17}
\]

or

\[
k_c(T; t^\circ) = \frac{\ln(C_0/C_t)}{\rho(T) t}, \tag{18}
\]

where \( K_c(T) \) – specific reduction rate COD, l/(g · h);
\( C_0 \) and \( C_t \) – COD initial and current time \( t \), mg / l.

Then the COD reduction rate constant \( K_{ic} \) is

\[
K_{ic}(t^\circ) = 0.43 k_c(T; t^\circ) \rho(T). \tag{19}
\]

The results of calculating the constants values (Figure 2 b) show the identity of the BOD processes of the common and COD

According to the analysis method of \( BOD_5 \) total and COD, \( BOD_5 \) of the filtered sample was 20–25% of the total \( BOD_5 \), the presence of colloidal and finely dispersed suspended solids in the liquid was taken into account.

It has been experimentally confirmed that a decrease in \( BOD_5 \) and removal of COD is mainly determined by the retention of suspended solids. The removal of dissolved organics is associated with physicochemical and biochemical processes in the filter load, which provides from 5 to 25 a total decrease in \( BOD_5 \), depending on the filtering duration.

The obtained dependences allow calculating and optimizing the filtering parameters of tertiary treatment filters according to the existing method [10] according to the biochemical processes, taking place in the filter load.

Filtering parameters such as grain size of the feed \( (d_s) \), thickness of its layer \( (x) \), filtering speed \( (V) \), filter cycle duration \( (T_c) \) can be corrected, taking into account the required BOD in the filtrate. So, the total BOD in the source water \( (L_{s \text{ tot}}) \) is divided into BOD due to the content of suspended and dissolved organic substances \( (L_s) \) and \( L_d \) is determined by formula (13) at \( \beta=0.4 \). Then, \( L_d \) in the filtrate is calculated using formulas (6), (8), (10), with the parameters \( (T_s, t^\circ, \rho, t) \), established as a result of technological modeling [10], and the total BOD in the filtrate \( (L_{t \text{ tot}}) \) is determined according to the formula (13) taking into account the removal of suspension at \( \beta=1.0 \). If \( L_{t \text{ tot}} \) does not meet the sanitary norm, the filtering parameters are recalculated and adjusted.

Checking the oxygen regime of the filter robots is performed according to formulas (7), (9), (11) with the parameters of technological modeling \( (T_s, t^\circ, \rho, t) \). Normal biological activity of sludge occurs when the dissolved oxygen concentration is not less than 0.1 mg / l in the treated water [6,7]. If the calculated oxygen concentration in the filtered water is less than this value, anaerobic zones may form in the filter load. The place of their appearance can be specified by dependence (11), where \( t = x/V \). In this case, aeration of the treated water in the filter load or preliminary aeration is necessary. It is also possible to adjust the filtering parameters.

1. As a result of physicochemical and biochemical processes in the filter loads of tertiary wastewater treatment, the total BOD decreases by 5-25%, depending on the duration of the filtration.
2. The processes of biochemical oxidation of dissolved organics in the granular layer of the filter loading are characterized by the constants \( K_1 = 0.05 – 0.11 \text{ day}^{-1} \) and they are similar to processes in conventional biooxidants at low BOD values.
3. Equations for calculating \( BOD_5 \) due to dissolved organics and oxygen in the filter charge during the filter cycle are obtained. The oxygen regime in the filter charge is determined by the density of its saturation with sediment and the duration of the filter cycle.
4. The procedure for correction the calculated filtering parameters within biochemical processes is given.
5. Oxygen concentration increase in the treated water is necessary in order to intensify the process of biochemical oxidation in the filter loads.

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