Intensification of biological wastewater treatment in a bioreactor

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Abstract. The purpose of the research was to determine the inter regeneration period of immobilized sludge by changing the species composition and its viability on the “Brush” and “Contour” type loads, as well as to assess the specific speed of wastewater treatment in the presence of immobilized and free-floating sludge. With the use of additional biomass of sludge placed on a synthetic loading, biological treatment of wastewater is carried out by various cenoses of sludge suspended in the state, and biomass attached to the loading. A synthetic loading was placed in the experimental cell of the bioreactor, where the activated sludge was sedimented. A fine-bubble aerator for aeration of the water-sludge mixture was placed at the bottom of the experimental cell. The situation of long-term operation of the bioreactor with synthetic loading with immobilized sludge without its regeneration was simulated. The kinetics of the species composition of immobilized sludge on synthetic inert loading was studied. The specific rate of wastewater treatment was calculated, and the time of the inter regeneration period of the sludge immobilized was determined. The kinetic dependence of the species composition of the biocenosis of immobilized sludge was obtained. The optimal time of the inter regeneration period for synthetic loading of the “Brush” type was determined 5–6 days, for the loading of the “Contour” type – 3–4 days. After these periods of time, a reduction in the specific rate of wastewater treatment begins, and there is also the possibility of secondary pollution of treated water. Mathematical expressions of the dependence of the specific cleaning rate on time for various types of loading are obtained.

Introduction

Wastewater treatment in bioreactors using immobilized biocenosis, fixed on inert materials, allows to achieve the required quality of wastewater treatment, creates the security of immobilized microorganisms from the effects of negative technological factors. With the use of additional biomass of sludge placed on a synthetic loading biological treatment of wastewater is carried out by various cenoses of sludge state in the suspended, and biomass attached to the loading. The material and form of the biomass carrier affect the number of immobilized microorganisms [1, 2].

The use of inert loading, immobilizing sludge up to 15±20 g/l.m., makes it possible to increase the oxidative capacity of the bioreactor, increase the resistance of biological structures to instantaneous discharges of toxic substances, stabilize the process of wastewater treatment, increase the depth of biological treatment and reduce the volume of aerated sewage treatment plants [3–6].

For the stable operation of the bioreactors that make up the treatment plant, various types of loading materials are used. In the experiment, synthetic loadings such as “Brush” and “Contour” were used as carriers of immobilized biomass. The sludge immobilized on them requires periodic renewal,
since spontaneous removing of the biomass does not occur when it dies off. Hydrodynamic flows with a speed of ~ 0.5 m/s along the perimeter of the bioreactor do not wash off the biomass. In the zone in which inert loading is established, the flow velocity of the liquid is ~ 0.05 m/s and lower, therefore the immobilized biomass is reliably fixed on the loading and becomes covered with mucus over time, causing secondary contamination of the treated water [7–9]. It is necessary to carry out periodic regeneration of immobilized sludge in order to update it.

**Experimental part**

The purpose of the research was to determine the interregeneration period of immobilized sludge by changing the species composition and its viability at the “Brush” and “Contour” type loads (Fig. 1), as well as to assess the specific speed of wastewater treatment in the presence of immobilized and freely floating sludge.

![Figure 1. Synthetic loading: a – “Ruff”; b – “Contour”.

The experimental setup consisted of a model cell made of a polyethylene pipe with an internal diameter of 100 mm and a height of 1 m (Fig. 2).]
Figure 2. Scheme of the experimental setup: 1 – polyethylene pipe; 2 – metal stand; 3 – metal tube for regeneration; 4 – brush loading; 5 – microcompressor; 6 – fine bubble aerator; 7 – rotometer; 8 – compressor with receiver; 9 – rotameter.

The pipe (1) was mounted on a metal stand (2) in a vertical position. A metal tube (3) with a diameter of 10 mm was placed in the pipe for air regeneration of the brush loading covered with immobilized sludge. Brush loading (4) with a diameter of 50 mm and a length of 0.7 m was attached to the upper and lower ends of the tube, bent at right angles. At the lower end of the tube there were 4 holes, 2 mm in diameter, for the implementation of air medium-bubble regeneration of the brush loading. As an aeration system for a water-sludge mixture, the AEN-4 microcompressor (5) was used, providing a specific aeration intensity of 8.15 m³/(m²·h), a fine-bubble aerator (6) and a rotameter PM-0.63 GUZ (7) to control air flow. The aerator was located under the brush loading. Regeneration of loading (4) was provided by a compressor with a receiver (8) and controlled by a PM-6.3 rotary flowmeter (9). A water-sludge mixture was poured into the cell in a volume of 7.85 dm³ with a dose of sludge 2÷3 g/dm³, BOD₅ varied in the range of ~ 280÷380 mg/dm³.

To determine the species composition of the biocenosis and its viability, two days later, a sample of a certain mass was taken and dissolved in 0.1 dm³ of water. Microscopic analysis was carried out using an electron microscope LEICA DM 1000.

To determine the number of microorganisms in immobilized sludge, a multistage method of calculating a calibrated drop was applied O.G. Nikitina [8]. The calculation is carried out in three stages, but for operational control limited to the first two.

To determine the number of organisms \( K \) (pcs./mg) of the investigated sludge in the sample, the formula was used

\[
K = \frac{3}{V_k \cdot m} \tag{1}
\]

where \( \Theta \) – number of copies, pcs.; \( V_k \) – drop volume (0.01 ml); \( m \) – mass sludge dose, g/dm³, equal to

\[
m = 10 \cdot (m_2 - m_1), \tag{2}
\]

где \( m_1 \) – mass of the empty jar, g.; \( m_2 \) – mass of the jar with the dried sediment, g.

The counting of microorganisms for each stage was carried out three times to reduce the random experimental error. To calculate the number of organisms \( K \), an arithmetic mean rounded to an integer was used.
Discussion of the results

The observation data for the period of the experiment, i.e. the period of immobilized sludge on various synthetic loadings, are summarized in Table 1.

| The day of sampling in the experiment, days | number of microorganisms, pcs./0,1dm$^3$ | loading “Brush” | loading “Contour” |
|------------------------------------------|------------------------------------------|----------------|-----------------|
| 1                                        | 400                                      | 398            |                  |
| 3                                        | 418                                      | 406            |                  |
| 5                                        | 430                                      | 410            |                  |
| 7                                        | 433                                      | 380            |                  |
| 9                                        | 300                                      | 298            |                  |

In accordance with the data of Table 1, dependences were constructed showing the dynamics of the number of viable microorganisms (Fig. 3).

![Figure 3](image_url)

**Figure 3.** The dynamics of the number of microorganisms immobilized sludge on synthetic loading: 1 – “Brush”; 2 – "Contour".

When finding the load “Brush” in the bioreactor, the number of microorganisms decreases during the experiment from 400 pcs. up to 300 pcs. by power dependence and is described by the equation

$$K = -1,354t^3 + 14,75t^2 - 36,86t + 425,2,$$

where $K$ is the number of microorganisms, pcs.; $t$ is the time of the experiment, day.

For seven days, there was an increase in the number of dominant microbial species in the volume of immobilized sludge. During this period, the synthetic load was covered with a dense non-removable biomass, which was not penetrated by oxygen from the water-sludge mixture. This led to a decrease in the number of aerobic microorganisms, and the dependence is extreme in nature with a clear maximum on the seventh day. Therefore, the regeneration of the immobilized sludge must be carried out until this moment, i.e. for 5-6 days. The subsequent sedimentation of sludge on the loading will lead to the appearance of immobilized sludge with preservation of all its active properties.

For synthetic loading “Contour”, the kinetic dependence has a weakly expressed diffuse maximum on the fifth day and is described by the following power expression

$$K = -0,5t^3 + 3,678t^2 - 3,785t + 398,4.$$

The regeneration of immobilized sludge on the loading “Contour” must be carried out before the fifth day.

It should be noted that the dominant composition of microorganisms immobilized sludge is identical in both cases. With the technologically proceeding wastewater treatment process, there were no numerically dominant species, or such dominance was minimal.
The initial composition of the active immobilized sludge at the loading was presented quite fully (Fig. 4): Hypotricha, Stentor polymorphus, Arcella, Lapadella ovlis, Suctoria, Ciliata.

![Hypotricha](image1)
![Stentor polymorphus and Arcella](image2)
![Epistylis](image3)
![Lapadella ovlis](image4)
![Suctoria](image5)
![Oligohymenophora](image6)

**Figure 4.** Microscopic analysis of the species diversity of the biocenosis of immobilized sludge on a synthetic loading on the first day of the experiment.

The wide species diversity of activated sludge organisms (at least 25 types of protozoa) testified to the good state of the biological system of the bioreactor, the high efficiency of wastewater treatment, and the adaptation of the biocenosis to the negative effects of toxic substances in wastewater [11, 12].

Microscopic analysis of the activated sludge species composition shows the ecological structure with high taxonomic diversity without the numerical predominance of various species. Small colorless carrying flagella, filamentous bacteria, small forms of both bare and shell amoebas are almost completely displaced from the biocenosis or their numbers are minimal. From ciliates prevails the type of gastropod and attached forms, whose vital activity is associated with a fairly well-formed flocculated active sludge. There are representatives of the highest level – predators, which positively affects the degree of purification of water from organic pollutants by increasing the intensity of exchange. In immobilized nitrifying sludge, Suctoria (not reaching mass development), carnivorous rotifers, worms of the genus *Chaetogaster* and predatory *Fungi* are always present. Often there are *Tardigrada* [13–15].

On the ninth day of the experiment, a marshy putrid odor appeared. The species compositions of the attached sludge and its viability have changed significantly (Fig. 5). *Nematodes* appeared, indicating the decay of immobilized sludge. The benthos amoeba cysts, microscopic *Algae* and *Arcella* are widely represented.
Microscopic Algae

The benthos amoeba cysts

**Figure 5.** Microscopic analysis of the species diversity of the biocenosis of immobilized sludge on a synthetic loading on the ninth day of the experiment.

To assess the cleaning ability of the resulting biocenosis, the BOD₅ value was monitored. Sewage analyzes were conducted in the testing laboratory of water quality biological treatment plant no.1 of OJSC ANHK, Angarsk.

The specific removal rate of pollutants reflects the biochemical essence of the process of pollution consumption and their oxidation by active sludge of various biocenoses. The specific removal rate of pollution is the amount of pollution that can be removed 1 g of dry sludge ash-free substance in one hour under the specified conditions for the implementation of the biochemical treatment process. The value of this parameter was determined for two types of synthetic loading.

The specific cleaning rate \( \rho \) was calculated by the formula

\[
\rho_i = \frac{(L_{en} - L_{ex})}{a_i(1-S)\cdot t_a} \left( \frac{\text{mgBOD}_5}{\text{g·h}} \right),
\]

where \( L_{en} \) – BOD₅ начальное, \( \text{mg/dm}^3 \); \( L_{ex} \) – BOD₅ конечное, \( \text{mg/dm}^3 \); \( a_i \) – доза ила, \( \text{g/dm}^3 \); \( S \) – зольность активного ила, 0,3; \( t_a \) – время очистки, 1 ч.

The experimental data and the calculated values of the purification rate are listed in Table 2.

| The day of sampling in the experiment \( t \), days | Loading “Brush” | Loading “Contour” |
|---|---|---|
| \( L_{en} \), \( \text{mg/dm}^3 \) | \( L_{ex} \), \( \text{mg/dm}^3 \) | \( a_i \), \( \text{g/dm}^3 \) | \( \rho_i \), \( \text{mgBOD}_5/(\text{g·h}) \) | \( L_{en} \), \( \text{mg/dm}^3 \) | \( L_{ex} \), \( \text{mg/dm}^3 \) | \( a_i \), \( \text{g/dm}^3 \) | \( \rho_i \), \( \text{mgBOD}_5/(\text{g·h}) \) |
| 1 | 280 | 133 | 5 | 42,00 | 280 | 135 | 5 | 41,43 |
| 3 | 314 | 132 | 6 | 43,33 | 321 | 144 | 6 | 42,14 |
| 5 | 383 | 162 | 7 | 45,10 | 330 | 121 | 7 | 42,65 |
| 7 | 381 | 118 | 8 | 46,96 | 257 | 110 | 6 | 35,00 |
| 9 | 228 | 110 | 6 | 28,10 | 246 | 151 | 5 | 27,14 |

The graphical interpretation of the obtained dependences of the change in the specific cleaning rate during the course of the experiment is shown in Fig. 6, 7. The mathematical dependences of the dynamics of the cleaning rate for various types of loading are presented in the corresponding figures.
Figure 6. Dynamics of the specific speed of wastewater treatment in the presence of immobilized sludge on the synthetic loading "Brush".

From the presented graph (Fig. 6) it can be seen that the specific speed increases slightly over seven days. The maximum is clearly pronounced, and corresponds to the seventh day, further dynamics shows a decrease in the value of the cleaning rate. Before the onset of this moment it is necessary to make regeneration of the immobilized sludge. The optimal time of the inter regeneration period is 5-6 days. Cyclic regeneration of sludge at brush loading leads to the appearance of active immobilized sludge.

For synthetic download the "Contour" the dynamics of changes in specific speed wastewater treatment (Fig. 7) has a weak maximum on the fifth day. Regeneration is required before this moment, i.e. on 3-4 day.

Conclusion

As a result of the experiments, data were obtained, on the basis of which it can be concluded that the optimal time of the inter regeneration period, for synthetic loading of the “Brush” type is an interval of 5-6 days, for loading of the “Contour” type – 3-4 days. After these periods of time, a reduction in the specific rate of wastewater treatment begins, and there is also the possibility of secondary pollution of treated water.

Mathematical expressions for time dependence of the specific wastewater treatment rate for various types of loading are obtained.
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