Modeling a biological wastewater treatment system

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Abstract. The treatment of domestic wastewater of housing and communal services and the subsequent use of separation products are one of the important environmental problems of our time, its solution contributes to resource conservation and the development of non-waste (green) technologies. The article described the design of the local treatment station, for which centralized sewage systems are not provided, including an aeration tank and a secondary sump with an aeration system for regulating biological processes. For regeneration of the biocenosis in the aeration tank, there is a recirculation system for activated sludge accumulated in the secondary sump. The rational composition and organization of the biological wastewater treatment process ensure deep destruction of biogenic elements and efficient deposition of the dispersed phase. A mathematical model of the probability of particle deposition in a secondary sump during a free flow with a free surface is proposed, which allows predicting the composition of the settled and not trapped dispersed phase and determining the degree of purification of the liquid phase, considering the productivity and deposition surface of the apparatus and technological parameters of the effluents. By the method of simulation modeling, the local degrees of particle deposition in the secondary sump, calculated for an average nominal diameter \( d_0 \) of 25 and 20 \( \mu \)m, were estimated. Established that a decrease in \( d_0 \) from 25 \( \mu \)m to 20 \( \mu \)m makes it possible to increase the integral degree of wastewater treatment from the dispersed phase from 87% to 94%, but the surface of the secondary settler increases by more than 1.5 times.

1. Introduction

The treatment and disposal of domestic effluent generated as a result of human activity constitute one of the important environmental problems of our time and in this direction various physicochemical and biological methods for their purification have been developed. It is the possibility of regulating the degree of removal of the dispersed phase that led to the creation of various engineering and technological solutions, the efficiency criteria of which are the degree of purification, that is, the environmental factor, and the cost of resources for their implementation - the economic factor [1, 2].

With the growth of suburban settlements, the arrangement of land plots with private houses issues of modernization, reconstruction and construction of new collectors, reduce energy costs for the transportation of wastewater to wastewater treatment plants have become particularly important. In this regard, studies aimed at improving decentralized local systems, providing treatment of domestic wastewater in places of their accumulation and, accordingly, reducing the technogenic load on ecosystems, are in demand by society and production [3, 4]. Such systems should have compact...
dimensions, be environmentally friendly, and the quality of the cleaning products should be possible to use, in particular, the purified liquid phase for irrigation of crops [5, 6, 7] and deeply processed excess sludge as an organic fertilizer [8, 9].

At present, local treatment facilities operating on the principles of biological destruction of biogenic elements and precipitation of the dispersed phase, have the need for regular emptying of sewage machines, transporting effluents to central treatment facilities for further processing. However, this technology does not allow the use of wastewater treatment products within the formation zone for technical or agricultural needs [10].

Thus, the aim of the study is to develop a compact module for the biological treatment of domestic wastewater for individual residential facilities, providing deep destruction of biogenic elements and the possibility of using separation products for beautification and landscaping of urban and rural areas, and mathematical model of fractional capture of the dispersed phase in this apparatus.

2. Methods and materials
The biological treatment system for domestic wastewater can be formalized in the form of the model shown in figure 1. Here, traditionally for such technologies, the destruction of dissolved organic and non-oxidized mineral compounds is carried out by the biocenosis of microorganisms in the bioreactor, including aeration tank and secondary sump and regulation of these processes is achieved by aeration. The regeneration of the biocenosis in the aeration tank is carried out by recirculation of activated sludge accumulated in the secondary sump.

![Figure 1. Model of a biological wastewater treatment system.](image-url)

In accordance with the model of the biological wastewater treatment system, a pilot module was designed [10] and manufactured, representing a vertical tank with a sealed bottom (figure 2, a). When the module is mounted in an existing septic tank, a station with two technological zones is formed: aeration tank and a secondary sump. The walls of the existing septic tank serve as the station case (figure 2, b). All elements of the module are made of polymeric materials and the case (functionally performing the work of a secondary sump) from polypropylene sheets. The module is equipped with a mini-compressor for the aeration system and airlift operation. Air is supplied to the aeration elements via PVC hoses from the air distribution tank. To regulate the performance of aerators, the supply pipelines are equipped with shutoff fittings.

The pilot module was manufactured at LLC NPO «ORTECH-Housing and Public Utilities», Volgograd, Russia. The module was mounted in an existing septic tank in a private home.

The sediment was taken using airlift with a diameter of 25 mm, which was installed in the secondary sump so that the suction end is lowered to the required depth to the maximum permissible standing layer. The wet sediment was dried artificially in an oven under vacuum, the fractional
composition of the dispersed phase was determined by sieve analysis. In the developing of the mathematical model used deterministic factor analysis.

![Figure 2](image)

**Figure 2.** Module (a) and station (b) for biological treatment of domestic wastewater with a capacity of 1 m$^3$/day [10].

### 3. Results and discussion

The effectiveness of the biological treatment plant can be estimated by the integral (total) degree of capture of the dispersed phase in the secondary sump, when the biogenic elements have already been destroyed.

To compilation a mathematical model, we will accept the boundary conditions - particles entering the secondary settler immediately acquire a stationary deposition rate, their residence time $\tau_p$ corresponds to or more than their deposition time $\tau_{os}$[11]:

$$d\tau_p \geq d\tau_{os}.$$  

(1)

The surface of the secondary sump, taking into account the volumetric flow rate $q_v$ (m$^3$/s) and the stationary deposition rate of particles of nominal diameter $\omega_0$ (m/s), is determined by the dependence:

$$F \geq \frac{q_v}{\omega_0}.$$  

(2)

Since the particles have a polydisperse composition in wastewater, the deposition rate must be calculated on the average nominal particle diameter $d_0$ (m). Then, particles of size $d_i \geq d_0$ are captured 100%, and particles of size $d_i < d_0$ are not completely captured.

To determine the probability of capturing a dispersed phase with size $d_i$, it is necessary to know the critical height $h$ in the secondary settling tank, on which these particles have time to sediment to its bottom (figure 3). The profile of the velocity portable movement of such particles, taking into account the profile of the average velocity $\bar{\omega}$ (m/s) and the height of the liquid layer $H$ (m), is described by the equation [11]:

$$\bar{\omega}_j = 3 \cdot \bar{\omega} \left[ \frac{z}{H} - 0.5 \left( \frac{z}{H} \right)^2 \right].$$  

(3)

Since the speed of the portable movement depends on the coordinate of the height $z$, then equation (1) in differential form takes the form:

$$\frac{dx}{\bar{\omega}} \leq \frac{dz}{\omega_j}.$$  

(4)
after division of variables and integration, taking into account formulas (3) and \( x = L \) (distance coordinate or length of the secondary sedimentation sump), we obtain:

\[
\bar{\omega} = \left[ 1.5 \left( \frac{h}{H} \right)^2 - 0.5 \left( \frac{h}{H} \right)^3 \right] \leq \frac{\omega_j \cdot L}{H}. \tag{5}
\]

![Figure 3. The velocity profile of the transport of particles in a free flow with a free surface.](image)

A particle entering the secondary sump, may be with equal probability in any of its height, then the geometric complex characterizes the probability of capturing the dispersed phase of size \( d_j < d_0 \), i.e., the local degree of capture:

\[
\chi = \frac{h}{H} \leq 1. \tag{6}
\]

For particles of sizes \( d_0 \) and \( d_i \geq d_0 \), the value \( \chi = 1 \), i.e., they are captured 100%, even getting to the very top disadvantageous to capture the trajectory, where \( h = H \).

Inequality (5) for the case \( d_i \geq d_0 \), \( \omega_i \geq \omega_0 \) and \( h = H \) written as:

\[
\bar{\omega} \leq \frac{\omega_0 \cdot L}{H}. \tag{7}
\]

We tie the probability of capturing the dispersed phase of size \( d_j < d_0 \) with the rate of their deposition, dividing on each other the inequalities (5) and (7):

\[
1.5 \cdot \chi^2 - 0.5 \cdot \chi^3 = \frac{\omega_j}{\omega_0}, \tag{8}
\]

or based on Stokes’ law:

\[
1.5 \cdot \chi^2 - 0.5 \cdot \chi^3 = \left( \frac{d_j}{d_0} \right)^2. \tag{9}
\]

Then, the fractions of trapped particles of each fraction, taking into account their local capture rates \( \chi \) and \( C_u \) concentrations, are calculated by the equation:

\[
C_y = \chi \cdot C_u. \tag{10}
\]

Accordingly, the integral degree of wastewater treatment is the sum of the fractions of captured particles of each fraction \( u \):

\[
\eta = \sum_{u=1}^{n} C_y. \tag{11}
\]

Using the method of simulation modeling, we will evaluate the local degrees of capture of the dispersed phase in the secondary sump, calculated on the average nominal diameter \( d_0 = 25 \mu m \), when the known distribution density fractions (figure 4).
Figure 4. Density of the distribution of particles by fractions in domestic wastewater and the proportion of captured particles (the region of non-captured particles is hatched).

According to the developed mathematical model, particles of \( d_i \geq 25 \ \mu m \) in size are captured 100%, and particles of size \( d_i \) are not completely captured (figure 4, a). Then, knowing the ratio \( d_i / d_0 \), the local degree of capture of particles with a size of 20 microns will be 74% \( (\chi_{20} = 0.74) \), 15 \( \mu m \) - 54% \( (\chi_{15} = 0.54) \), and 10 \( \mu m \) - 35% \( (\chi_{10} = 0.35) \). The integrated degree of wastewater treatment in the secondary sump according to the formula (11) will be equal to:

\[
\eta = 0.35 \cdot 0.05 + 0.54 \cdot 0.1 + 0.74 \cdot 0.2 + 0.3 + 0.25 + 0.1 = 0.87.
\]

Let us estimate the local degree of particle capture in the secondary sump, calculated on the average nominal diameter \( d_0 = 20 \ \mu m \) (figure 4, b), for the case when, for example, \( \eta = 87\% \) does not satisfy the conditions for reuse of the liquid phase. Then particles of \( d_i \geq 20 \ \mu m \) in size are captured 100%, 15 \( \mu m \) - 69% \( (\chi_{15} = 0.69) \), 10 \( \mu m \) - 45% \( (\chi_{10} = 0.45) \), and the integral degree of purification will be equal to:

\[
\eta = 0.45 \cdot 0.05 + 0.69 \cdot 0.1 + 0.2 + 0.3 + 0.25 + 0.1 = 0.94.
\]

4. Conclusion
The developed compact module for private households, including aeration tank and secondary sump, due to the rational layout and organization of the biological treatment of domestic wastewater provides deep destruction of biogenic elements, which contributes to improving the environmental well-being of rural and urban areas, improving people’s living standards, resource conservation, development of non-waste technologies.

The mathematical model of the probability of trapping the dispersed phase in the secondary sump during a free flow with a free surface allows predicting the composition of the captured and non-captured particles and determining the degree of purification of the liquid phase, taking into account the productivity and deposition surface of the apparatus and technological parameters of wastewater. When designing a local biological wastewater treatment plant, it is must to take into account the necessary integral degree of capture of the dispersed phase, since, for example, a decrease in the average nominal diameter of particles captured by 100% from 25 \( \mu m \) to 20 \( \mu m \) according to equation (2) and the stokes law will lead to an increase in the surface of the secondary sump by more than 1.5 times.

5. Acknowledgments
The publication has been prepared with the support of the grant of the President of the Russian Federation no MD-311.2020.11
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