Gas-hydrodynamic characteristics of aerotanks

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Abstract. The purpose of the research was to determine the hydrodynamic indicators of aerotanks determining the depth and effectiveness of wastewater treatment. The study of technological parameters of the aeration tank was carried out on a physical model representing a transverse vertical section of the aerotank. The hydrodynamic similarity in the model and industrial aerotank determined by the identical values of the Reynolds, Froude, and Euler criteria. The study of similar indicators on an industrial aeration tank is very difficult and costly. The model and experimental setup make it possible to vary in a wide range the intensity of air aeration, the design and location of the aerator, control the speed of hydrodynamic flows and the concentration of freely floating sludge in the facility with aeration. To study the gas-hydrodynamic indicators in the aerotank model, original methods based on the laws of physical chemistry have been developed and used. The contact surface of the phases "liquid - gas" from the intensity of air aeration was determined using a chemical method for aerated biological wastewater treatment facilities. The dependences of the specific contact surface of the phases "liquid - gas", referred to the unit of the working area of the aerator, on the intensity of aeration and the depth of immersion of the aerator are obtained. The oxidizing ability of a fine bubble aerator was determined for various aeration intensities. The dependences of the oxidizing ability on the contact surface of the phases "liquid - gas" in aerotanks were obtained for the first time. It is shown that the oxidation ability of the aerotank is determined by the phase contact surface and, to a large extent, by the hydrodynamic situation in the aerotank, which forms the fields of freely floating activated sludge.

1. Introduction

Wastewater treatment in aerotanks, using a free-floating active biocenosis, allows to achieve the required quality of wastewater treatment, reducing the anthropogenic load on surface water sources. For the stable operation of the aeration tank, which is part of the biological treatment facilities, it is necessary to ensure a uniform distribution of oxygen and silt throughout the volume of the aerated structure [1–3].

The gas-hydrodynamic situation in the aerotank to a large extent determines the effectiveness of wastewater treatment. The direction and speed of hydrodynamic flows and activated sludge suspended in it, as well as the concentration of dissolved oxygen, are determined by the type and intensity of aeration and the location of the aerators in the aerotank. The aeration system provides the supply and distribution of air oxygen to the aerotank, which is necessary to maintain the oxidation of pollutants entering the biological treatment, maintaining activated sludge in a state of suspension, and also blowing off the gases formed as a result of metabolism, the excess of which inhibits the process of biochemical wastewater treatment [4–6].
The possibility of physical modeling of gas-hydrodynamic processes in aerated wastewater treatment plants as a first approximation was determined by the ratio between four dimensionless complexes [7–9]:

\[ E_u = X \cdot Re^{-s} \cdot Fr^{-r}, \]

(1)

where \( E_u, Fr, Re \) – are the Euler, Frood, and Reynolds criteria, respectively; \( X \) – constant.

The Euler criterion reflects the effect of the difference in hydrostatic pressure on fluid motion, and its value characterizes the ratio of the change in hydrostatic pressure to the inertia force at similar points. The Froude criterion reflects the influence of gravity or dead weight on fluid motion and is a measure of the ratio of inertia to gravity at similar points. The Reynolds criterion reflects the influence of the friction force on the fluid motion, and its value characterizes the ratio of inertial forces to the friction forces in such flows [7, 8].

Providing a developed contact surface of the "liquid - air" during aeration makes it possible to increase the oxidation power of the aerotank, stabilize the mineralization of wastewater, increase the depth of biological treatment and provide floating activated sludge with aerobic conditions [8–12].

2. Experimental part

The purpose of the research was to determine the hydrodynamic indicators of aerotanks that determine the depth and effectiveness of wastewater treatment using a fine-bubble aerator installed in the corner of the aerated structure. To study the gas-hydrodynamic processes and the distribution of activated sludge in aerated structures, an experimental setup was created with a model cell (figure 1), which is a vertical transverse section of the aerotank (figure 2).

The cell was made of polished silicate glass and had dimensions of \( 0.06 \times 0.77 \times 0.88 \) meters. The amount of air supplied by the compressor to the cell was controlled by valves, and the instantaneous air flow was controlled by a rotameter of the RM 0,63 type GUZ [8, 9, 12]. AKVA-LINE aerator consisted of a perforated hull with radial holes. Its dispersant is made in the form of a cylindrical shell of a composition of two grades of porous polyethylene, which ensures contact of air with liquid directly in the upper coating layer. The technology of creating a dispersing coating provides fine-bubble aeration. The coating forms air bubbles, the average size of which remains unchanged or even decreases with increasing air flow [8].

The interfacial surface of the gas-liquid system is an important calculated value, which depends on the geometry of the structure, the conditions of its functioning and the physical properties of the liquid.
The mass transfer rate of oxygen from air of liquid a can be easily changed by changing the interphase surface [5, 8, 13, 14].

The chemical method [8–10, 13, 14] for determining the surface of the contact of phases is based on the known chemical reaction rate. It allows you to determine the integral surface of the contact of phases regardless of the structure of the two-phase layer moving in the structure. To determine the contact surface of the phases "liquid - gas", the absorption rate of carbon dioxide by an aqueous alkaline solution of sodium hydroxide was studied. The change in alkali concentration was determined by titration of an alkali solution with decinormal hydrochloric acid [8, 10, 14].

Studies to determine the oxidative ability of pneumatic aeration using the AKVA -LINE fine bubble aerator were carried out on a model of an aeration tank filled with tap water, the aerator was installed in the working position, at the bottom of the model in the corner. Sodium sulfite and a catalyst cobalt chloride were used to remove oxygen from water [8, 11]. To determine the concentration of oxygen in water, an ATT–3010 oxygen meter was used. The oxidizing ability of the aerator (gO2/h) was determined by the equation [4, 5]:

\[
OC = \frac{Kq \cdot a \cdot C_o \cdot V}{1000},
\]

(2)

where \(Kq\) – volumetric mass transfer coefficient, 1/h; \(C_o\) – limiting concentration of oxygen in water at an infinite aeration time at a given atmospheric pressure, water temperature and its salinity, mg/dm³; \(V\) – volume of water in the cell, dm³.

To study the hydrodynamics in the physical model of the aeration tank, with the intensity of fine-bubble aeration \(J = 5.41 \text{m}^3/(\text{m}^2\cdot\text{h})\) with a lateral aerator, we used the tracer method based on the introduction of solid particles with the same density in the water as the density of water [6, 8, 15]. Particles moved along with the fluid flow, which, when using video in a planar two-dimensional model, made it possible to analyze the velocity of any fluid element with its decomposition into components along the coordinate axes.

To determine the scalar and vector values of the wastewater circulation velocity at the \(i\)-th space point of the model of the vertical transverse section of the aeration tank (see figure 1), a control square of 80×80 mm was selected, the coordinates of the mark \(x_1\) and \(z_1\) at the input and \(x_2\) and \(z_2\) were fixed the exit from this square, as well as the time \(t\) of finding the mark in this control square.

Speed components were calculated as:

\[
\vec{V}_{i,x} = \frac{(x_2 - x_1)}{t}, \quad \text{cm/s};
\]

(3)

\[
\vec{V}_{i,z} = \frac{(z_2 - z_1)}{t}, \quad \text{cm/s}.
\]

(4)

Since the true velocity is a pulsating quantity, and \(\vec{V}_{i,x}\) and \(\vec{V}_{i,z}\) are averaged quasistatic components, to determine the latter, we controlled the movement of 10–15 label particles at each studied point of the model. The distribution of the components of the circulation velocity at a given point was close to the normal law. The medians of the distribution curves coincided with an accuracy of 5% with the arithmetic mean values, which were used in the future to construct a quasi-static vector field.

Velocity modulus values were calculated as

\[
|V_i| = \sqrt{(\vec{V}_{i,x})^2 + (\vec{V}_{i,z})^2}.
\]

(5)

When constructing vector and scalar velocity fields, the area of the vertical cross-sectional model of the aeration tank was divided into 10 horizontal (1 – X) and nine vertical (1 – 9) sections. Plots of the velocity components \(V_x, V_z\) and of velocity modules \(|V|\) water were obtained for each of the processed sections in MS Excel, and vector and scalar fields of the fluid circulation velocity were constructed using the CorelDraw graphical editor [6, 8].
The distribution of free-floating sludge in the cross section of the aeration tank was studied by constructing the sludge distribution fields in the aeration tank model with a lateral arrangement of a finely bubble aerator. We used the method of light absorption, measuring the intensity of the light flux in 320 control squares measuring 40×40 mm. From the difference in the readings of the intensity of the stream passing through the sludge mixture and clean water, the integral value of the loss of light flux intensity attributable to activated sludge was found [6, 8]. To translate the difference in light flux intensities into a dose of activated sludge, a calibration plot of the dependence was constructed. For the experiments, sludge taken from the secondary settling tanks at the left-bank sewage treatment facilities of the city of Irkutsk was used. The silt index, which characterizes the sedimentation ability of sludge, was \( \approx 150 \text{ cm}^3/\text{g} \).

3. Discussion of the results
The dependences of the specific contact surface of the phases, referred to the unit of the working surface of the aerator, on the aeration intensity of the lateral fine bubble aerator for various liquid levels in the aeration tank model, are presented in figure 3.

![Figure 3](image-url)

**Figure 3.** The dependence of the specific contact surface of the phases, referred to the unit of the working surface of the aerator, on the intensity of aeration, with a lateral arrangement of a fine-bubble aerator, for the depth of the aerotank model: ■ – 0.8 m; ▲ – 0.4 m.

With an increase in aeration intensity from 2 to 7 \( \text{m}^3/(\text{m}^2\cdot\text{h}) \), the specific contact surface of the phases increases, approximately three times, for the given depths of the aeration tank model. These dependencies are linear and are described by the following equations:

\[
A_{(0.8)} = 2.0315 \cdot J - 0.2156, \quad (6)
\]

\[
A_{(0.4)} = 1.6357 \cdot J - 0.1854. \quad (7)
\]

The use of the aeration tank model with a depth of 0.4 m leads to a 25% reduction in the value of the specific contact surface of phases, referred to the unit of the working surface of the aerator, at any aeration intensity.
The dependence of the oxidizing ability (OC) of a fine bubble aerator on the specific intensity of air aeration is linear and is described by the equation: \( OC = a \cdot J \), and the tangent of the angle of inclination of the straight line to the abscissa axis is determined by the depth of the aeration tank model (figure 4).

With a depth of the aeration tank model of 0.8 m, the angular dependence coefficient is \( a = 0.5121 \), and at a depth of 0.4 m, the dependence of the oxidizing ability on the aeration intensity is smoother and \( a = 0.3082 \).

Figure 4. The dependence of the oxidizing ability of a fine bubble aerator AQUA-LINE on the intensity of aeration with a lateral arrangement of the aerator for the depth of the aeration tank model: ■ – 0.8 m; ▲ – 0.4 m.

From the analysis of the dependence, it can be concluded that it is advisable to increase the depth of immersion of the aerator in the aerotank in order to increase the oxidizing ability. The use of a square cross-section of the aerotank also contributes to an increase in oxidizing ability compared to a rectangular cross-section. This is due to the twisting of gas bubbles in the circulating flow of water and the increase in the time of mass transfer of oxygen.

The vector (figure 5) and scalar fields (figure 6) constructed according to the results of research at a fine-bubble aeration intensity \( J = 5.41 \text{ m}^3/(\text{m}^2 \cdot \text{h}) \), with the lateral arrangement of the aerator, show field inhomogeneity over the area of the cross-sectional section of the aerotank.

The range of water velocity values varied from 0.6 to 0.05 m/s and less. The highest numerical values of the velocity are realized along the perimeter of the circulation circuit, decreasing towards its central zone. In the center of the contour, the speed is 10—12 times less than along its perimeter and the center of the contour coincides with the geometric center of the model of the vertical transverse section of the aerotank. The velocities in the corner zones of the cell are ~2 times smaller than the maximum water velocity, which is explained by the chaotic motion of the water flows during rotation in the circulation circuit.

The numerical values of the flow rates of sewage in the vertical cross section of the aerotank obtained by us are in good agreement with the only published data [4]. According to these data, taking into account the heterogeneity of the field, the flow velocity varies from 10 cm/s to 70 cm/s with a lateral arrangement of the aerator in the aeration tank. It should be noted that there is no information on the intensity of aeration and the design of the aerotank in the literature.

An extensive "stagnant zone" in the central region of the aerotank cross-section model, in which speeds of 5±10 cm/s of water flows are realized, promotes rapid coagulation of activated sludge into large agglomerates. The low flow rates do not contribute to the delivery of dissolved oxygen to the
stagnant zone, however, they are sufficient to maintain activated sludge in state of suspension. The oxidizing ability of this area of the aerotank, which depends on the surface of the “liquid – sludge” contact, decreases. This area is ~20÷25% of the entire cross-sectional area of the aerotank.

Thus, a fourth of the volume of the aeration tank is derived from the process of active oxidative ability of organic substances.

Figure 5. Vector field of water flow velocity in the aeration tank model.
Figure 6. Scalar field of water flow velocity in the aeration tank model: Δ – 5 cm/s; ▲ – 10 cm/s; ○ – 15 cm/s; ● – 20 cm/s; ⋆ – 25 cm/s; ◊ – 30 cm/s; ♦ – 35 cm/s; □ – 40 cm/s; ■ – 45 cm/s; ★ – 50 cm/s; ♣ – 55 cm/s; ○ – 60 cm/s; ♦ – 65 cm/s.

A comparison of the numerical values of the water velocities obtained during the simulation and measured on aeration tanks with a distributed water supply of the Left-bank sewage treatment facilities in Irkutsk allows us to use physical modeling to study the gas-hydrodynamics of the aeration tank.

The distribution field of floating sludge along the vertical cross section of the aerotank, with a lateral arrangement of a fine bubble aerator at a dose of activated sludge $a_1 = 3$ g/dm$^3$, is characterized by an uneven distribution of sludge over the section of the aerotank. The area of maximum sludge concentration (interval $3÷3.1$ g/dm$^3$) has an irregular annular shape and occupies the central peripheral part of the aerotank [6, 8].

In the areas of the model adjacent to the walls, bottom and surface of the wastewater, the concentration of sludge is $2.9÷3.0$ g/dm$^3$. This region is characterized by maximum fluid velocities of $0.45÷0.60$ m/s (see figure 5).

Inside the ring-shaped form, a concentration drop is observed from $2.9$ to $2.4$ g/dm$^3$, and the realized velocities have a minimum value of $\sim 0.1$ m/s and less. A decrease in the rate of fluid circulation in the center of the ring promotes coagulation of activated sludge with the formation of large flakes, crushed in water jets with a high speed (figure 7).
Figure 7. Plane field of activated sludge distribution in a vertical cross-sectional model of the aerotank at a fine-bubble aeration intensity $J = 5.41$ m$^3$/m$^2$·h).

A three-dimensional image of the obtained field of distribution of activated sludge clearly shows the uneven distribution of sludge over the vertical cross section of the aerotank (figure 8).

The sludge-water mixture in the aeration tank is a heterogeneous (multiphase) system, in which the biologically purified wastewater serves as the dispersion medium, and the activated sludge flakes are formed as a complex three-level cellular structure surrounded by an exocellular substance of biopolymer composition. The precipitation of flocs of activated sludge (when its concentration in the sludge mixture is more than 0.5–1 g/dm$^3$) occurs with the formation of a visible phase boundary between the clarified water and sludge.
Figure 8. Three-dimensional and planar distribution fields of activated sludge in a vertical cross-sectional model of the aerotank at a fine-bubble aeration intensity $J = 5.41 \text{ m}^3/\text{(m}^2\text{h})$. The concentration of activated sludge is given in g/dm$^3$.

For the sludge index values $I_l = 150$ cm$^3$/g and a dose of activated sludge $a_l = 3$ g/dm$^3$, the rate of decrease in the interface between the clarified water and sludge is 7.23 mm/s, which is much lower than the flow rates along the perimeter of the circulation circuit and, to a first approximation, coincides with its center.

Our analysis of the molecular kinetic properties of the colloidal system made it possible to prove that, for a given aeration intensity, $J = 5.41 \text{ m}^3/\text{(m}^2\text{h})$ and $a_l = 3$ g/dm$^3$, the sludge flakes move in the flows of the circulation circuit, providing the oxidation power of the aerotank.

4. Conclusion
An experimental setup with a model cell representing a vertical cross section of an aerotank is proposed for studying gas-hydrodynamic processes and the distribution of activated sludge in aerated structures. The possibility of physical modeling of gas-hydrodynamic processes on the aerating plants of wastewater treatment as a first approximation is shown.

The contact surface of the phases "liquid - gas" was determined using a chemical method for on the aerating plants of wastewater treatment from intensity of air aeration. The dependences of the specific contact surface of the phases, referred to the unit of the working surface of the aerator, on the intensity of aeration and the depth of immersion of the aerators are obtained. Dependencies are linear. Mathematical expressions obtained.

The oxidative capacity of a fine-bubble aerator for different aeration intensities of a water-silt mixture was determined. The dependences are linear, the tangent of the angle of inclination of the lines to the abscissa axis is determined by the depth of the aerotank model.

For the first time, the dependences of the oxidizing ability on the contact surface of the phases "liquid - gas" were obtained. It was shown that the phase contact surface does not completely determine the oxidation ability of the aerotank. The hydrodynamic situation in the aeration tank, which forms the fields of activated sludge, is very important for the oxidative ability of the aerotank.

The obtained vector and scalar fields of fluid velocities at the lateral position of a small-bubble aerator show the inhomogeneity of the velocity field in the model of the vertical cross section of the aerotank. The maximum velocity of fluid flows is realized in the main circulation circuit and reaches $\sim 60$ cm/s. There are “stagnant zones” in the center of the aerotank model, with fluid flow rates of 10
cm/s or less. These speeds, however, are sufficient to maintain activated sludge in state suspension. In the stagnant zone, sludge flakes coagulate, which reduces the intensity of the oxidative process of organic pollution in this zone, reaching ~25% of the model area of the vertical section of the aerotank.

An analysis of the molecular kinetic properties of the colloidal system showed that for a given aeration intensity \( J = 5.41 \text{ m}^3/\text{(m}^2\cdot \text{h}) \) and a dose of activated sludge \( a = 3 \text{ g/dm}^3 \), the sludge flakes move in the flows of the central circulation circuit providing the oxidative power of the aerotank.

The distribution fields of activated sludge are obtained in the vertical cross-sectional model of the aerotank with a lateral arrangement of a fine-bubble aerator. The non-uniform distribution of silt over the cross section of the aerotank model is shown. The area of maximum sludge concentration has an irregular annular shape and occupies the central peripheral part of the aeration tank model. The central stagnant zone is characterized by active coagulation of sludge into large agglomerates, which reduces the "liquid-sludge" surface, which determines the oxidation of organic substances in the aerotank.

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