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Experimental Testing of Water Body Aeration Airlift Technology

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ABSTRACT

The article is devoted to substantiation of parameters of water body aeration technology at high, as well as low, air temperatures. As a result of studies, the design of the water aerator based on a two-stage airlift has been improved. A study of its physical model has been conducted. The cost indicators of the set-up and its components have been obtained. It has been established that at various design parameters, the proposed scheme of operation allows to oxygenate water more effectively when compared to conventional design. A new type of water aerator based on two-stage airlift has been proposed. The linear dependence of the dynamics of the aerator flow rate on the supply of compressed air by the compressor, as well as the logarithmic dependence regarding the water oxygenation have been established. The indicator of effective rate, which allows for evaluating efficiency of water body oxygenation has been substantiated. The study results open the possibility of using an aerator with improved design to prevent eutrophication of water in open water and industrial reservoirs, e.g. in construction.

Keywords: eutrophication, aerator, airlift, water oxygenation, compressed air, compressor.

INTRODUCTION

Providing quality water in water bodies and other waters of Ukraine has become the most urgent task. Sewage entering the hydrographic network significantly affects the indicators of abiotic factors of the aquatic environment, thus leading to changes in the physical and chemical, as well as biological, properties of water. The result is violation of the hydrochemical regime and living conditions of all ecological groups of aquatic organisms, from protozoa to fish. The availability of potable, agricultural, technological and other types of water resources directly depends on the environmental conditions in the water body. According to the approved standards of water quality for water bodies, the indicator of the dissolved oxygen has to make not less than 4 mg/dm. Climatic conditions, such as warming of water above 25°C in summer and freezing in winter, contribute to the reduction of dissolved oxygen in water, which leads to the development of anaerobic biota and other negative effects. This is of considerable practical importance in various industries, like construction. The presence of 'blooming' products in the water for preparation of cement mortars leads to a deterioration of the growth conditions of crystals in concrete and, therefore, to a decrease in their strength. Therefore, the study to maintain the quality of aquatic ecosystems for the conservation of biological resources, especially of potable water, is a vital issue.

Anthropogenic activity is traditionally considered the main source of pollution of surface water bodies. With the growth of industry, such substances as compounds of nitrogen, potassium, phosphorus enter the water, along with the wastewater of cities, enterprises, waste and sewage from livestock facilities (Padedda et al., 2017). Moreover, industrial wastewater has higher temperature and cause thermal pollution when entering the water bodies.

Rising temperatures and excess biogenic substances in water bodies cause the active development of blue-green algae, with their biomass accumulating in the coastal part and decomposing. As a result, the content of oxygen and nutrients decreases, which leads to the emergence of such processes as eutrophication and ‘blooming’ of water (Bashutsʹka, et al., 2020; Sluše et al., 2015). Optimum thermal water conditions (12–22 °C) within a biopurification plant at the territory of a closed-down mine have been determined theoretically and confirmed experimentally; the conditions provide year-round 32% decrease in total salt content of water as well as 35% decrease in the amount of suspended matters (Kostenko et al., 2018).

Dissolved oxygen is the connecting element between the organic and mineral components of water bodies. Its volume depends on ambient temperature and atmospheric pressure. In summer, when the water and air temperatures are high (from 25°C), a phenomenon of thermal stratification occurs in water bodies, with the formation of a thermal layer, a thermocline, where oxygen is practically insoluble. This phenomenon prevents the vertical mixing of water and, as a result, an area of oxygen deficiency, hypolimnion, is formed under the thermocline (Huang et al., 2019).

Above the thermocline, oxygen deficiency, high temperature and light create an ideal environment for the active development of anaerobic blue-green algae, which form a dense layer on the water body surface and block access of sunlight and airflow to benthic aquatic organisms. Photosynthesis of lower algae ceases, which in turn leads to accumulation of CO_2, with its excess causing the death and decomposition of fish with the formation of hydrogen sulphide and ammonia (Yang et al., 2015).

Aeration is an effective method of solving the problem of oxygen deficiency in water to improve the conditions of the aquatic environment. Aeration of water bodies is one of the main conditions for the normal functioning of the aquatic ecosystem. It is required both in summer and in winter, since the formation of ice on the surface of the water body also reduces the content of dissolved oxygen.

The aeration can be biological, chemical and mechanical. Biological aeration includes the use of mineral fertilizers to stimulate the development of phytoplankton, which is a natural source of oxygen in water bodies. The disadvantage of biological aeration is the inability to control the development of phytoplankton. Chemical aeration includes the use of chemical reagents that are able to emit oxygen when they interact with water. The main disadvantage of the chemical method of aeration is the need to strictly adhere to the proportions of the reagents, since their excess in the water body can lead to chemical poisoning of aquatic organisms. Therefore, mechanical aeration seems promising, since it consists in the use of technical devices, aerators that promote water oxygenation (Solomin et al., 2013).

Based on their operation, there are surface, injector, wind-powered, combined, and bottom aerators. Bottom and combined aerators are usually used for fisheries, which, unlike injector and wind-based aerators, do not have rotating and moving parts that can damage fish.

Surface aerators, which spray water over the surface of the water body similar to fountain, have become commonly used (Wesołowski et al., 2015). However, the disadvantage of such aerators is the impossibility of their use at minus air temperatures due to freezing of the sprayed water and the formation of ice grains. Another disadvantage is the low efficiency at air and water temperatures above 25°C. In this case, oxygen is very sparingly soluble in warm water due to its physical properties. Moreover, the partial pressure of oxygen also significantly reduces in heated air, and it cannot quickly diffuse into the water. Therefore, due to water heating, the efficiency of aeration by spraying is low, and the threat of eutrophication remains.

The principle of operation of airlift aerators is as follows: air is supplied through the nozzles, which are usually located at the bottom of the water body, creating vertical movement of water and mixing water from the bottom layers with water from above layers, thus oxygenating the lower layers when they contact atmospheric air (Abdelwahed, 2013).

The intensity of saturation of the water body with dissolved oxygen depends on the diameter of the bubbles supplied by the aerator. It is believed that the smaller the diameter of the bubbles, the better the gas exchange of the water body (Deendarlianto et al., 2018).

Summarizing the available data, the issue of solving the problem of aeration of water bodies at minus temperatures in winter and at high temperatures above 25°C in summer can be considered of great importance.

The purpose of the study is to improve the technology of aeration of water bodies using airlifts.

To achieve this objective, the following tasks have been solved: (i) design and testing of a two-stage airlift set-up model, (ii) study of effect of the airlift constructive parameters on hydrodynamic indicators of water-air streams, (iii) assessment of the impact of airflow costs on the dynamics of water oxygenation.

RESULTS

Based on the analysis of known methods and means of aeration of water bodies, the creation of a set-up where water is oxygenated and its temperature is maintained not higher than 25°C is required. Furthermore, the authors hypothesized that the intensity of gas exchange between air and water in the airlift depends on the time during which the bubbles are pressurized near the bottom of the water body. To observe the limitations given, the authors proposed a scheme of an airlift aerator (Kostenko et al., 2021), which is shown in Figure 1.

The design is based on a two-stage airlift. Water with low oxygen concentration passes through the water intake pipe, which is located below the level of the thermocline in summer and below the depth of freezing of the water body in winter. Through the strainer (1), which removes large suspended solids and aquatic organisms that can interfere with the proper operation of the unit, water enters the geothermal heat exchanger (2). Here the water reaches the temperature, suitable for dissolving oxygen, and hence the comfortable existence of aerobic aquatic organisms, of 10–15 °C. Then water enters the mixing chamber (3), where compressed air from the air duct (6) is supplied through the spray nozzle (4), and then the gas-water (foam) mixture enters the airlift (5). The diameter of the chamber is larger than the airlift column, which determines the moderate velocity of its movement and, therefore, increases the duration of contact of air in the bubble with water. The air supply is carried out by means of an air duct (6) from the compressor (7), which is powered by a wind turbine (8). The compressor and the wind turbine are mounted on the foundation (9) for stability.

The essence of the proposed technical solution is to intensify the transition of oxygen from air bubbles to water in the mixing chamber. In a geothermal heat exchanger, the water temperature is set close to the temperature of the bottom layers of the water body, which is usually within 5...20°C. The solubility of oxygen in water with such temperature is much higher than in heated water. This is facilitated by the relatively low velocity of eutrophicated water and the relatively high partial pressure of oxygen in the air bubbles

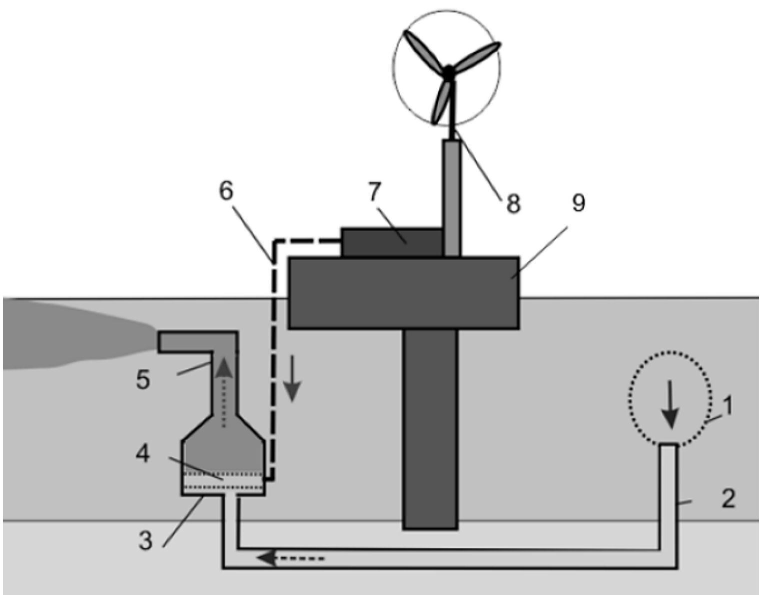

Figure 1. Schematic construction of the airlift aerator: 1 – strainer; 2 – geothermal heat exchanger; 3 – mixing chamber; 4 – spray nozzle; 5 – airlift; 6 – air duct; 7 – compressor; 8 – wind turbine; 9 – foundation

at the depth of the mixing chamber. Oxygenated water enters the upper layers of the water body, which prevents its eutrophication. The use of wind as a source of energy can significantly reduce operating costs to ensure comfortable conditions for aquatic organisms.

Experimental verification of the efficiency of water oxygenation, the dynamics of oxygenation from the compressor supply, and the design parameters of the proposed set-up was carried out by physical modelling. The laboratory set-up (Fig. 2) consisted of compressor (1), air duct (2), which passes into the air spray nozzle (3), mixing chamber in the form of a pipe with a diameter of $Ø_1$ = 30 mm (4), which is connected by a conical adapter to the airlift column, a pipe with a diameter of $Ø_2$ = 11 mm (5). All elements of the aerator airlift (items 3–5) are made of transparent material and immersed in a glass container filled with water.

The laboratory model operates as follows: by means of a compressor (1), through the air duct (2), air enters through a spray nozzle (3), which forms swarms of air bubbles of small diameter and supplies them into the mixing chamber (4), where there water is intensively mixed with air, creating conditions for oxygenation. In an airlift aerator, the density of the water-air mixture is much lower than the density of water, therefore it is pushed up. As the mixture rises to the surface and its pressure decreases, the surface area of the bubbles and the partial pressure of oxygen decrease significantly relative to the volume, and its dissolution in water decreases.

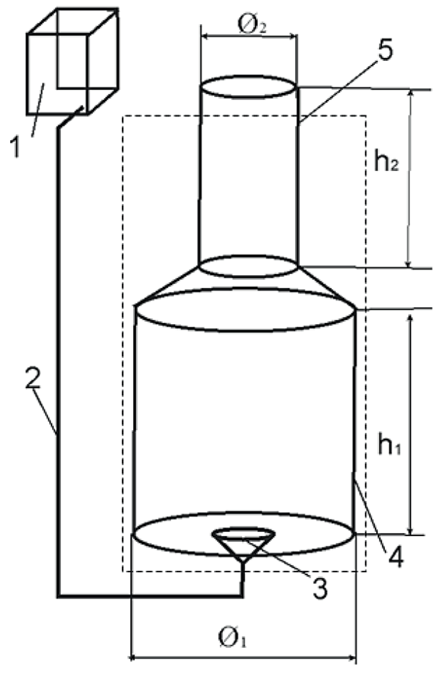

Figure 2. Scheme of the laboratory set-up:
1 – compressor, 2 – air duct, 3 – air spray nozzle,
4 – mixing chamber (diameter $Ø_1$, length h_1),
5 – airlift column (diameter $Ø_2$, length h_2), dotted line – transparent container filled with water

To inhibit the process of water degassing, the mixture enters the airlift column (5), where, with increasing pressure due to decreasing pipe diameter, flow rate increases, and oxygenated water together with air bubbles enter the surface layers of the water body, preventing their eutrophication. During the experiment on the aeration of water bodies, three options of the airlift with different sizes of the airlift column were used. The dimensions of the mixing chamber were constant, it had a diameter of $Ø_1$ = 30 mm and a length of h_1 = 400 mm. The airlift column had a diameter of $Ø_2$ = 11 mm, and the length had three options: I – h_2 = 600; II – h_2 = 400; III – h_2 = 200 mm.

The laboratory set-up of the aerator airlift was connected to a *Bezan PANDA* 0.15 kW compressor with a maximum capacity of up to 23 L/min, which provided four fixed modes of air supply through the spray. The flow rate of water supplied by the airlift was determined by supplying it to the measuring vessel. The filling time of the vessel, as well as the period of movement of air bubbles on each section of the airlift was measured using an electronic stopwatch, *XiaomiRedmi 9 Pro* model. In this case, 15 measurements were performed for the reliability of experimental data.

The movement of air bubbles in the pipes was observed visually, the time of movement on individual sections of the model was controlled, the velocity of the bubbles was recorded in visible parts of the airlift (opaque part of the conical adapter is 50 mm from the chamber and 50 mm from airlift column), the process was video recorded. The oxygen content in the water was estimated using indicator paper with an accuracy of ±1%. To evaluate the efficiency of the proposed design with the conventional aerator, the dynamics of water oxygenation was compared. An airlift air spray nozzle was used as a conventional aerator. The main cost indicators of the laboratory set-up were evaluated (Table 1).

The data show that the unit efficiency Q_u increases with increasing compressed air supply, which can be explained by a decrease in the density of the air-water mixture (foam) in the airlift column, and the viscosity of the foam with increasing air content. There was an increase in

Table 1. Laboratory set-up cost indicators

Aerolift aerator parameters	Design options		
Lower pipe diameter $Ø_1$, mm	30		
Lower pipe length h_1, mm	400		
Upper pipe diameter $Ø_2$, mm	11		
Upper pipe length h_2, mm	600	400	200
Consumption of air Q_p at different modes of compressor operation, $m^3/s \cdot 10^{-6}$	177.17		
	193.27		
	201.43		
	211.34		
Consumption of water Q_v at corresponding modes of airlift operation, $m^3/s \cdot 10^{-6}$	2.50	5.71	5.41
	6.25	7.72	22.86
	19.40	20.85	26.67
	25.90	21.91	38.09
Consumption of foam, air-water mixture Q_u at corresponding modes of airlift operation, $m^3/s \cdot 10^{-6}$	179.67	182.88	182.58
	199.52	200.99	216.13
	220.83	222.28	228.10
	237.24	233.25	249.43

foam flow with a decrease in the linear dimensions of the upper stage, which is associated with a decrease in the hydrodynamic resistance of the hydraulic path of the set-up. A striking indicator of aerator performance is the movement of air bubbles in certain parts of the structure. To calculate the velocity of bubbles, which reflects the flow rate of the foam, an experiment was performed on three set-up options. In the first one, the ratio of the length of the lower stage to the upper was $h_1/h_2=1:1.5$, in the second – $h_1/h_2=1:1$, in the third – $h_1/h_2=2:1$. The average travel time of air bubbles along individual stages of the set-up, which was then used to determine the velocity of movement of bubbles, was measured (Table 2).

The results of the experiments showed that the velocity of the air bubbles is linearly related to the airlift performance. When comparing the velocities of travel of bubbles in the mixing chamber in all three options of the set-up, the largest velocity is observed in the third option, and in the first and second they are almost the same, and by 0.1–0.08 m/s smaller (Fig. 3*a*).

A linear dependence on performance is also observed in the airlift column; the velocity of the bubbles is the greatest in the first case and in the second and third it is by 2–2.5 m/s less (Fig. 3*b*). Some increase in the velocity in the airlift column at the compressor maximum fourth mode of air supply is due to a sharp change in the viscosity of the water-air medium. The amount of air in the foam significantly prevails over water amount.

Under to the accepted hypothesis, the water oxygenation depends on the duration of contact of air bubbles with water, other things being equal. Therefore, the total time of movement of bubbles

Table 2. Velocity of bubbles in the airlift aerator model

Stage diameter, mm	30	11	30	11	30	11	30	11
Column length 600 mm								
Supply of liquid through the airlift, m^3/s	$2.5 \cdot 10^{-6}$		$6.25 \cdot 10^{-6}$		$19.4 \cdot 10^{-6}$		$25.9 \cdot 10^{-6}$	
Average bubble travel time, s	2.29	1.78	2.28	1.65	1.81	1.33	1.49	0.98
Velocity, m/s	0.15	0.31	0.15	0.33	0.19	0.41	0.23	0.56
Column length 400 mm								
Supply of liquid through the airlift, m^3/s	$5.71 \cdot 10^{-6}$		$7.72 \cdot 10^{-6}$		$20.85 \cdot 10^{-6}$		$21.91 \cdot 10^{-6}$	
Average bubble travel time, s	2.16	2.15	1.96	1.66	1.62	1.32	1.42	1.09
Velocity, m/s	0.16	0.16	0.18	0.21	0.22	0.26	0.25	0.32
Column length 200 mm								
Supply of liquid through the airlift, m^3/s	$5.41 \cdot 10^{-6}$		$22.86 \cdot 10^{-6}$		$26.67 \cdot 10^{-6}$		$38.09 \cdot 10^{-6}$	
Average bubble travel time, s	1.70	1.35	1.37	1.10	1.30	0.87	1.22	0.69
Velocity, m/s	0.21	0.14	0.26	0.17	0.27	0.22	0.29	0.28

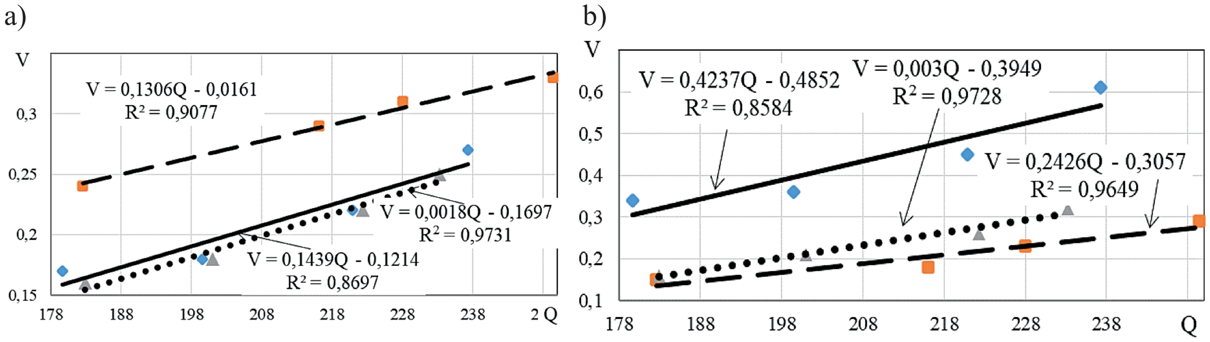

Figure 3. Velocity of air bubbles (V, m/s) in the mixing chamber (a) and the airlift column (b) depending on the performance of the set-up (Q_u, m³/s·10⁻⁶). Solid, dotted, dashed lines – respectively I, II, III options of the airlift design

through the set-up was calculated as the sum of the periods of travel of bubbles through the mixing chamber and the airlift column (Table 3)

The time during which the bubbles exist in the set-ip can be reliably approximated by a linear decreasing function (Fig. 4).

In addition to the duration of contact of water with oxygen in the set-up, its performance is essential. The so-called effective set-up rate (**O**) was calculated as a fraction of the water flow division (Q_y, $m^3/s \cdot 10^{-6}$) by the time of bubble movement (t, s) at the corresponding modes of supply (Q_p, $m^3/s \cdot 10^{-6}$) of air by the compressor (Fig. 5). Effective rate **O**=Q_y/t is a quantitative indicator, which allows for evaluating the amount of water in contact with the air in the set-up per unit of time.

The data shown in Figure 5 demonstrate that the highest indicators were obtained when using the third option of the set-up with a small size of the airlift column. In the other two options, the indicators were by 3–3.7 times smaller and almost the same, the difference was 1–1.2%.

The method of determining oxygen in water using reagents was used in the experimental set-up to measure the water oxygenation. The experiment was performed with the second mode of the compressor supply; water flow Q_y for the first option was $6.25 \cdot 10^{-6}$, m^3/s, for the second – $7.72 \cdot 10^{-6}$, and for the third – $22.86 \cdot 10^{-6}$, m^3/s. Boiled water with a minimum oxygen content was poured into the outer vessel of the experimental set-up with a volume of three litres, the initial concentration was 2 mg/L. Water was sampled for oxygen concentration analysis every five minutes.

For the first 30 minutes, there was an intense water oxygenation, and then its increase slowed down (Fig. 6). The maximum oxygen value was 7–8 mg/L; this is due to the fact that at a given temperature, pressure and volume of the closed system of the experimental set-up, water oxygenation was maximum possible.

Therefore, during long-term operation of the unit for aeration of limited volume of water, water oxygenation is ensured, the dynamics of the process is described by a logarithmic equation. During three hours of compressor operation, the oxygen concentration increased more than 3.5 times. A comparison of the dynamics of this process with almost threefold differing airlift supply modes, indicated that in the third mode with the largest airlift supply, the oxygenation rates were the highest. All set-up options have found more efficient dynamics of water oxygenation than the that for the conventional aerator design.

DISCUSSION

Regarding the obtained hydrodynamic indicators of the aeration unit, they indicate (Table 1) an increase in foam production and, therefore, water supply, in proportion to the increase in

Table 3. Total time (s) of movement of bubbles along the set-up

Design option	Compressor supply Q_p, $m^3/s \cdot 10^{-6}$			
	177.17	193.27	201.43	211.34
I	4.07	3.93	3.14	2.47
II	4.31	3.62	2.94	2.51
III	3.05	2.47	2.17	1.91

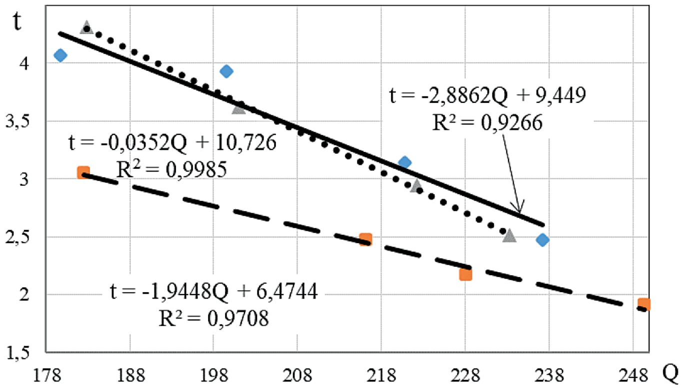

Figure 4. Time (t, s) of travel of bubbles through two stages at different operating modes of the set-up (Q_u, m³/s·10⁻⁶). Solid, dotted, dashed lines – design options I, II, III, respectively

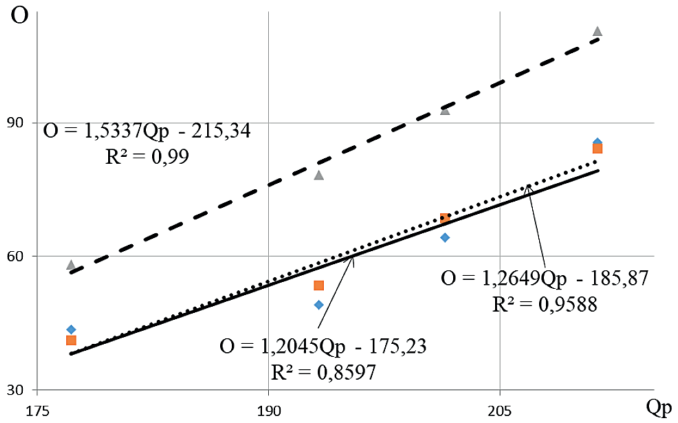

Figure 5. Effective set-up rate (**O**) when changing the operating modes of the compressor (Q_p, m³/s·10⁻⁶). Solid, dotted, dashed lines – design options I, II, III, respectively

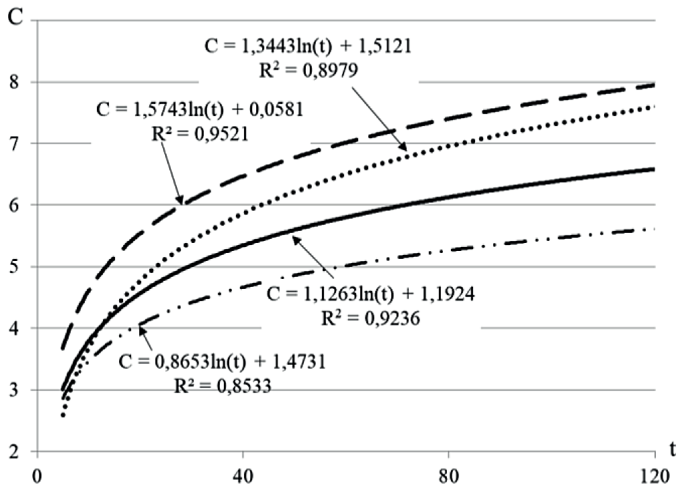

Figure 6. Dynamics of water oxygenation (C, mg/L). Solid, dotted, dashed lines – liquid supply by airlift (Q_y,m³/s·10⁻⁶), respectively, 6.25, 7.72 and 22.86, dashed-dotted line – conventional aerator, (t, min) duration of aeration,

compressed air flow rate. The set-up option with lower hydrodynamic resistance of the airlift column, i.e. at h_2 = 200 mm, provided the highest efficiency of the set-up. Increasing the length of the second stage of the set-up leads to an increase in hydrodynamic resistance.

Consideration of the indicators of velocity of air bubbles given in Table 2 shows the following.

In the set-ups with relatively high hydrodynamic resistance, namely when the length of the airlift column is longer than the length of the mixing chamber, at $h_2/h_1>1$, the velocity of air bubbles in the mixing chamber is lower than at $h_2/h_1<1$, which determines greater efficiency in the third option (Fig. 3*a*). In the airlift column, the greater length of the second stage determined the greater ejection effect, therefore, the velocity of air bubbles was the highest (Fig. 3*c*). It is not obvious that an increase in the geometric dimensions of the airlift columns determines a reduction in the time of contact of air with water; according to the accepted hypothesis, this may determine a decrease in mass transfer in the airlift column. Therefore, at the ratio h_1/h_2= 1:1.5, the velocity is lower in the first stage and the velocity is increased in the second stage. At the ratios h_1/h_2=1:1 and h_1/h_2=2:1, the opposite effect is observed. To ensure oxygenation, it will be more effective to use the ratio of the lengths of the pipes where the wide part will be shorter, i.e. close to the ratio h_1/h_2=2:1. Under these conditions, the air bubbles will travel in the first stage of the airlift longer, which will provide better air exchange of water with air, and thus create an effective oxygenation.

Based on the received dependences, it is possible to come to a conclusion that efficiency of the set-up depends on air supply, and the ratio of velocities is defined by geometrical parameters of the design. The total time of movement of air bubbles in two stages of the set-up is also determined by both the design parameters of the set-up and the volume of compressed air supply by the compressor (Fig. 4). Moreover, there is an inverse linear relationship, when an increase in air flow rate leads to a reduction in contact between water and air.

The problem which consists of a certain contradiction between reduction of time of interaction of air with water and quantity of the foam formed by the set-up has been outlined. It is proposed to use the indicator of effective rate $\mathbf{O}=Q_y/t$, which allows for evaluating the amount of water in contact with the air in the set-up per unit of time (Fig. 5). The best results were obtained with the set-up third option with a small upper stage, in the other two they were almost identical and by 3–3.7 times smaller. It should be noted that qualitatively the picture of efficient rate is similar to the velocities of bubbles in the mixing chamber (Fig.3*a*)

Conducting an experiment on the efficiency of oxygenated confirmed the feasibility of operating with an efficiency rate of '**O**' to select a more efficient design option, especially in the initial, aeration period up to 10, min. The best performance was shown for the set-up third option (Fig. 6). Compared to the conditional aerator, all set-up options have demonstrated a more intensive mode of water aeration, which confirmed the feasibility of using this type of unit to prevent eutrophication of water bodies. The relative simplicity of the underwater part of the aerator, the absence of moving parts, increase the efficiency and reliability of the set-up when used in industry, such as construction and other areas.

CONCLUSIONS

Based on the theoretical preconditions for increasing the efficiency of water oxygenation and preventing its eutrophication, the physical model of the set-up with a two-stage airlift has been substantiated and investigated. According to the modelling results, the linear dependence of the velocities indicators of liquid and foam in some stages of the airlift on the air supply has been established. With increasing air supply, a higher flow rate of foam was observed in the column of the longer airlift, and the mixing chamber is characterized by the opposite conditions.

It has been established that the ratio of geometric dimensions between the stages of the airlift plays a dominant role in the formation of velocity flows. With the constant dimensions of the mixing chamber, the leading role of the dimensions of the upper stage has been established. The duration of the movement of bubbles in the air stages of the set-up has an inverse linear dependence on the supply of foam. With an increase in the supply of foam by 28% (from 178 to 283, $m^3/min_* 10^{-6}$) the time of travel of air bubbles in all set-up options was reduced to 60%.

To quantify the volume of water in contact with air per unit of time, it is proposed to use the efficiency rate $\mathbf{O}=Q_y/t$, which allows, in the first approximation, for evaluation of the efficiency of water body oxygenation. It has been experimentally established that the dynamics of water oxygenation by means of airlift is subject to logarithmic dependence; in laboratory conditions, the oxygen concentration was increased by 3.5 times within three hours.

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