The multifunctional power container. Water treatment

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Abstract. The results of studies of a multifunctional energy container are given. Investigated mixing of the fluid due to the rotation of the pneumatic-hydraulic aerator. The possibility of combining various technologies for wastewater treatment in one combined mobile structure is shown. Based on the conducted research, a wastewater treatment plant was proposed.

For energy supply and sewage treatment of villages, cottage settlements and even separate buildings it is necessary to build additional energy and sewage treatment plants, with associated complex design work [1]. In most cases, after deterioration or obsolescence of these stations, it is necessary to carry out major repairs and reconstruction or conservation, followed by the construction of new stations. It is also impossible to move them with reusing in case of a decrease in the number of subscribers of these stations or their complete disappearance for some circumstances. This is especially concerns the recreational areas, like The Baikal Nature Territory in the Irkutsk region.

Development and reconstruction of urban infrastructure is impossible without the reconstruction and modernization of sewage treatment plants. At the same time, the reconstruction and technical re-equipment of industrial and municipal wastewater purification facilities is one of the most difficult engineering tasks, which aimed at improving of the environmental situation
and protection of the water bodies from pollution and depletion. It's assumed, that within the urban development the stationary treatment facilities are designed and built. For to charge wastewater from nearby villages and cottage settlements, it’s necessary to build additional stations for wastewater receiving and sludge processing. There are many ways of polluted water treatment, but the most important factor is the fluid aeration and creation of aerobic conditions for biological treatment.

The fluid aeration is necessary for both to create flotation bubbles in the liquid and to saturate the liquid itself with oxygen, depending of the purpose of the chemical or biochemical process in water treatment, or another industries using aeration as the basis of the production cycle [2-5].

A variety of liquid aeration methods and devices for their implementation requires not only classification, but also a fundamental approach to the physical aeration patterns identification and creation of more sophisticated equipment and methods needed for various industries [6-11].

Various devices have long been used for dispersing air in a fluid in order to saturate it with air bubbles. This devices are called the aerators and classified according to various features [12-13]:

- Mechanical. The aerators, which have any moving (rotating) working member, implicating atmospheric air into the liquid phase;
- Pneumatic. This is tubing system, which supplies the aerated liquid with simple or technical oxygen saturated air under the pressure (directly or via dispersants);
- Pneumatic-mechanical (combined). Combining the design elements of the two types of aerators mentioned above;
- Hydraulic. It’s working principle is to use the kinetic energy of the fluid flow for the emergence of a developed gas-liquid contact surface.

In turn, each type of aerator is classified according to its design features.

When entering the atmosphere, the gas-liquid mixture with a high-speed movement represents filamentary and film formations into which liquid droplets were turned under the influence of a gas stream moving with this flow. Going below the liquid surface (submerged gas-liquid jet), a process of gas capture by liquid film particles and its immersion into the liquid volume in the form of bubbles is observed. Thus, by providing a fine spray of liquid into droplets of the same size, it is possible to achieve the formation of bubbles of a similar diameter, the size of which practically does not exceed that size of the bubbles generated by porous dispersants.

The liquid spraying process in a co-directed stream of gas (air) is closely connected with the aeration of the liquid and, accordingly, with biological methods of wastewater treatment and is promising for use in aerated lagoons.
The most of aerated lagoons are equipped with a pneumatic aeration system. Most often, these are diffuser plates, porous plastic and ceramic dispersants in the form of pipes, discs and etc., or steel perforated pipes. The main disadvantage of this aeration system is that the aerator pores are blocked by biological deposits from the outside and dust from the blown air from the inside (small bubble), and aerator openings are blocked by corrosion products (medium bubble), although to a lesser extent. There are created many designs of aerators of both classes, however, being improved versions of the previous devices, they do not combine the two main advantages of each other - fine air dispersion and a small degree of clogging. Not to mention the fact that neither one nor the other has a mixing capacity in various directions. There are various ways of the flow hydrodynamics control and stagnant zones prevention for modern aeration systems [7].

Pneumatic-hydraulic aerators (Fig. 1) are in the intermediate position between small and medium bubble aerators, because their dispersed composition of the gas phase varies from 0.1 to 10 mm, while most of the bubbles have close values of volume (2 to 4 mm), which positively affects the oxygen mass transfer process in liquid and the wastewater treatment process in general.

Insignificant clogging of aerators is associated with the absence of porous dispersants, on the one hand, and good flushing capacity of the gas-liquid jet, on the other. If necessary, it is possible to provide spring-loaded caps that are placed on the nozzles, which automatically close when the air and fluid supply are cut off, as well as simple technological openings at the lowest points of the system, working as air taps by analogy with the heating system.

High oxidizing ability in combination with a low degree of contamination and the ability to control hydrodynamics in the structure make pneumatic-hydraulic aerators promising aerating devices for biological wastewater treatment processes, due to the simplicity of its implementation, the achieved aeration quality and the absence of excessive energy consumption for its implementation.

Analysis of pneumatic-hydraulic aerators possible models

The study of various structures and theoretical models describing the two-phase flows hydrodynamics in these structures has made it possible to make the following assumptions. First, there is a mixing chamber in all models,
and in some cases, various dispersing devices located directly in the mixing chamber. Attempts to build a theoretical model of the different phases movement in such a chamber encounter serious difficulties, primarily due to the inability to determine either the state or the flow structure when mixing different phases.

![Figure 1](image-url)  
**Figure 1.** Pneumatic-hydraulic rotating aerator 1 – body; 2 – rod; 3 – mixing chamber; 4 – nozzle; 5 – inlet gas branch pipe; 6 – inlet liquid branch pipe.

Laboratory studies made up the main part of the work performed and included the optimal modes development, clarifying the physical nature of the processes occurring in the aerator, recording the main and auxiliary parameters of the operation modes under study.

The experimental research method was based as follows:
1) the water and air flow was measured;
2) the water and air pressure was measured;
3) the aerator number of revolutions was measured;
4) the air bubbles diameters was measured;
5) the oxygen water solubility in was measured.

Experimental studies of two-phase flows hydrodynamics in the aerator channel were carried out depending on the parameters of each phase at the entrance to the device channel. There were varied two basic parameters of the supplied fluid and air, first, the pressure and flow rate were adjusted, and then the pressure and flow rate of air were changed, secondly, the same parameters were changed, but already in a certain ratio (gas pressure - fluid pressure).
As can be seen from the results (Table 1), there is a clear dependence of the liquid oxygen saturation on the pressure in the system, associated increase of airflow, and the number of revolutions of the aerator, which create the mixing intensity.

Previously, the results of the pneumatic-hydraulic aerator experimental tests were presented in the form of charts showing the following relationships: "Number of revolutions - Pressure", "Gas flow - Pressure", "Liquid flow - Pressure". To build a dependence line for each parameter, an arithmetical mean value is taken for each stage of pressure increase.

The "gas-to-liquid" ratio, which is also one of the important pneumatic-hydraulic aerator parameters, was calculated as the ratio of air and water flow rates. This ratio is important for water purification and physico-chemical mineral processing [8, 12].

The results of the gas and liquid flows ratio changing experiments (Qg/Ql) depending on pressure, obtained on "pure" water, are shown in the chart (Fig. 2).

![Figure 2. The chart of dependence of the gas and liquid flows ratio from the system pressure.](image)

**Table 1.** Measurement results.

| №  | Pressure P, MPa | Gas flow Qg, dm³/min | Liquid flow Ql, dm³/min | Aerator number of revolutions N, 1/min | Gas bubbles diameter D, mm | O₂ liquid saturation, mg/dm³ |
|----|----------------|----------------------|------------------------|----------------------------------------|--------------------------|-----------------------------|
|    |                |                      |                        |                                        |                          |                             |
| 1  | 0.15           | 14.5                 | 14                     | 14                                     | 0.15                     |                             |
| 2  | 0.2            | 15                   | 15                     | 15                                     | 0.2                      |                             |
| 3  | 0.25           | 16.7                 | 16.7                   | 16.7                                   | 0.25                     |                             |
| 4  | 0.3            | 18                   | 18                     | 18                                     | 0.3                      |                             |
| 5  | 0.35           | 19                   | 19                     | 19                                     | 0.35                     |                             |
| 6  | 0.4            | 20                   | 20                     | 20                                     | 0.4                      |                             |
Fluid aeration studies and aeration devices selection have been conducted for a long time. The principle of aerating device operation was based on the general principles of hydrodynamic flows developed in the field of research of fuel nozzles.

It has been established that when a shock is created in the aerator, a fluid spraying mode in a coaxial gas flow occurs. Such optimization of the aerator design parameters allows the airflow to compress the jet annularly and the liquid to create a liquid flow cavitation regime, which then passes into a
film-dispersed liquid and airflows mode in the outlet nozzle. This flow mode will allow to further increase the airflow rate before the formation of a shock wave in the outlet nozzle, and after its breakthrough, the flow rate at the exhaust nozzle outlet reaches supersonic values. The airflow rate increasing with this flow mode will preserve the diameter of the flotation size air bubbles, which in turn will lead to an increased recovery during flotation.

The oxidation rate, or the oxygen consumption rate at a constant temperature at any given moment, is proportional to the organic substances mass in the water. Consequently, as the organic matter is oxidized, if there are no new impurities, the oxidation rate decreases all the time.

The oxygen dissolving process in water obeys the same law. Oxygen, like any other gas, can be dissolved in water only up to a certain volume that saturates water. This volume depends on temperature and pressure: higher the temperature, lower the oxygen solubility.

Showing dependence exists when oxygen is dissolved in air at a partial pressure corresponding to its content. The pure oxygen solubility at a higher pressure will be higher. Such a phenomenon is observed, as is well known, during the photosynthesis, when the green matter of plants, decomposing CO₂ into light, absorbs carbon and releases pure oxygen.

The oxygen dissolution rate, according to the law shown above, at any given moment is inversely proportional to the oxygen saturation degree of water or directly proportional to its under saturation (deficit). This applies, of course, only to the water-oxygen contact surface (diffusion layer). In order for this dissolution rate to relate to the entire water mass, it must be intensively mixed. Oxygen deficiency can be expressed in absolute values (in mg/dm³), as well as in relative values (in percent or in the total deficit fractions).

The scheme of the oxygen transfer from a gas bubble with a gas boundary film through the phase contact surface (gas-liquid), an additional film formed, for example, surfactants, the interface and the liquid boundary layer to the mixed liquid main mass was presented in the scientific works of B.N. Repin [4]. Next, the transfer of oxygen proceeds along the path of overcoming the liquid boundary film around the microbial cell, after which the oxygen enters the cell through the cell membrane.

The oxygen concentration profile is represented by a polyline, the steepness of which increases with the resistance to mass transfer in certain sections. Thus, at the site where molecular diffusion processes play a significant role, the rate of oxygen dissolution depends mainly on the phases contact surface area, determined by the size of gas bubbles, and the presence of contaminants in the liquid. At the site that has a gentle character and reflects the mainly convective diffusion influence, the oxygen concentration does not
change or slightly varies, since the hydrodynamics of real structures is characterized by a developed turbulence mode. And finally, on the final part, the slope of the oxygen concentration profile with the constancy of factors is mainly determined by the rate of its consumption by the microbial cell, which in turn depends on the nutrient supply rate, that is, on the process loads for organic pollution.

Thus, the oxygen dissolution process is inextricably linked with the process of its consumption.

Studies of fluid aeration in modeling the consumption active silt process (supply)

Pure water saturation with oxygen, which has previously been deoxidized with sodium sulfite with the presence of cobalt chloride, is the most common method of experimentally determining the aerator oxidizing ability and its associated performance parameters.

The sodium sulfite mass ratio and dissolved oxygen is 20 to 1, that is, 20 g of Na₂SO₃ are necessary for “binding” the 1 g of O₂. The expression of this form can be expressed by the following formula (1):

\[ m = \frac{20 \cdot C_o \cdot V}{1000}, \]

where

\[ m \] - sulfite mass, g; \[ C_o \] - dissolved oxygen initial concentration, mg/dm³; \[ V \] - deoxidized water volume, dm³.

The cobalt salt was not introduced as a catalyst, since the preparation time for the experiment was sufficient for the reaction to take place.

Before the experiment was started, a reference measurement of oxygen in water with an oximeter for 1 minute (always about 0 mg/dm³) was made, so as water temperature, as well as the thermometer and barometer room readings.

The data obtained during the experiment are recorded in a table, according to which the desired parameters are calculated.

To determine the oxidative capacity and efficiency, the following calculations were made.

Oxygen capacity, gO₂/h, is expressed with formula (2):

\[ OC = k \cdot C_s \cdot V, \]

where

\[ k \] – volumetric coefficient of mass transfer, 1/h;
\[ C_s \] – dissolved oxygen concentration limit at a given atmospheric pressure, the temperature of the water and its salinity, mg/dm³.
V – aerated water volume, dm$^3$.

Volumetric coefficient of mass transfer is expressed with formula (3):

$$k = \frac{2.303 \cdot [\lg (C_S - C_1) - 1\lg (C_S - C_2)]\cdot 60}{t}$$

where

$C_1, C_2$ – initial and end dissolved oxygen concentrations, respectively, mg/dm$^3$;

$t$ – time, min.

Dissolved oxygen concentration limit at a given atmospheric pressure (4), mg/l:

$$C_s = C_{s(760)} \cdot \frac{P_s - P}{760 - P}$$

where

$P_a$ – atmospheric pressure on the barometer, mm Hg;

$C_{s(760)}$ – oxygen concentration limit at an atmospheric pressure of 760 mm Hg, a given temperature $T$ and salinity $S$ of water, mg/dm$^3$, is expressed with formula (5);

$P$ – saturated steam pressure at a given water temperature, mm Hg (reference data).

$$C_{s(760)} = \frac{475 - 26.6 \cdot S}{33.5 + T}$$

The salinity (g/dm$^3$) was taken as a sodium sulfite mass ratio $m$ (g), required to deaerate a given water volume $V$, to this water volume (dm$^3$) (formula (6)):

$$S = \frac{m}{V}$$

Aerated water volume is expressed with formula (7):

$$V_a = V + Q_l$$

where

$V_a$ – aerated water tank volume, dm$^3$;

$Q_l$ – water volume, passing through the nozzle, dm$^3$ (for the pneumatic method $Q_l = 0$).

One of the most important technological parameters for evaluating the aerator performance is the ratio of oxidizing capacity to consumed power.

Aerator efficiency, g$\text{O}_2$/kWh (formula (8)):

$$\eta = \frac{OC}{N}$$

where

$N$ – energy expended by the engine compressor, kW.

Dissolved oxygen is one of the defining indicators for aerobic biological treatment facilities. Investigating the developed aerator, it is safe to say that it allows to saturate the liquid with air oxygen while simultaneously mixing it without significant technical expenses, so that the dissolved oxygen
spreads throughout the volume more efficiently and keeps the microorganisms in suspension. This makes it possible to consider this aerator more efficient and competitive among other devices for liquid aeration and to recommend it for implementation into sewage treatment plants in biological wastewater treatment facilities.

Biochemical wastewater treatment is carried out as a result of a complex set of interrelated physical, chemical and biological processes. As a result of laboratory research, a technological wastewater treatment system was created. This system involved a kit for ionometry, which allows to determine the pH and concentration of a number of ions, BOD and COD. The main non-metals in wastewater (methods for their purification), which involved in the experiment:

1. Ammonium Nitrogen (NH₄⁺): Biological filtration, oxidation with ozone, chlorine, alkaline and alkali-earth metals hypochlorites; aeration, sorption using sodium form zeolites, ion exchange resins, strong alkali treatment, flotation, ammonium reduction with metallic magnesium, addition of magnesium chloride solutions and trisodium phosphate.

2. Nitrate nitrogen (NO₃⁻): Electrodialysis, ion exchange resins, biological treatment, reverse osmosis, electroflotation, catalytic reduction to nitrogen.

3. Nitrite nitrogen (NO₂⁻): Biological filtration, oxidation by ozone, chlorine, alkaline and alkali-earth metals hypochlorites, hydrogen peroxide, reverse osmosis, ion exchange resins.

4. Sulfates (SO₄²⁻): Reverse osmosis, ion exchange resins, aluminum containing liming reagent.

5. Phenol (C₆H₅OH): Sorption, ozonation, mechanical cleaning, vapor-phase oxidation, liquid-phase cleaning, biological cleaning.

6. Phosphates (PO₄³⁻): Biological filtration, septic tanks, hydro cyclones, chemical cleaning, reverse osmosis, adsorption, ion exchange, coagulation, oxidation, followed by neutralization with lime milk, ozone, chlorine, and oxygen.

7. Fluorine: Reagent purification, sorption, reverse osmosis, ion exchange.

8. Chlorides (Cl⁻): Sorption, reverse osmosis, ion exchange.

Laboratory studies made up the main part of the work performed and included the optimal modes development, clarifying the physical nature of the processes occurring in the aerator, recording the main and auxiliary parameters of the operation modes under study, as well as changing the solution process, creating various model media in the tank.

The experimental research method was based as follows:
1) the water and air flow was measured;
2) the water and air pressure was measured;
3) the aerator number of revolutions was measured;
4) the air bubbles diameters was measured;
5) the oxygen water solubility in was measured.

The main variation of work:

Water comes from potable water supply system, and air is injected from the compressor with a pressure of 0.15 to 0.4 MPa. At first, it is necessary to pump the compressor to the required pressure with all valves closed. Then open the valves, the air begins to flow into the aerator, and then open the valve to supply water, adjusting the required pressure. The aerator starts spinning.

The system operation is recorded on a high-speed camera brand pco.1200s. This German production model allows to record high resolution and low noise videos. High-speed imaging allowed studying the multiphase medium flow dynamics and the jet development at the aerator channel exit into the test tank.

The data obtained during the experiment were recorded in Table 1, according to which the desired parameters of oxidizing ability and efficiency were calculated.

It was determined: the time of the experiment \( t \), min; aerated liquid volume \( V \), dm\(^3\); the sodium sulfite amount \( m \), g; the nitrogen nitrate amount \( m \), g; the ammonium nitrogen amount \( m \), g; the sulphates amount \( m \), g; the phenol amount \( m \), g; the phosphate amount \( m \), g; the fluorine amount \( m \), g; the chloride m amount, g; salt content \( S = \frac{m}{V} \), g/dm\(^3\); compressor engine capacity \( N \), kW; water consumption by water meter \( Q \), dm\(^3\); aerated liquid total volume \( V_l \), dm\(^3\); air flow by the rotameter \( Q_g \), dm\(^3\); system pressure \( P \), MPa; dissolved oxygen concentration, \( C_1 \), mg/dm\(^3\) at the beginning of the experiment; \( C_2 \) at the end of the experiment; air temperature \( T_g \), °C; water temperature \( T_l \), °C; current atmospheric pressure \( R_a \), mm Hg; saturated steam pressure \( P \) at the current liquid temperature, mm Hg; the water saturation limit with oxygen at a pressure of 760 mm Hg., so as current liquid temperature and salinity \( C_s \) (760), mg/dm\(^3\); the water saturation limit with oxygen at the current pressure \( C_s \), mg /dm\(^3\); oxygen volumetric mass transfer coefficient \( k \); oxidative ability of the environment, gO\(_2\)/h; average oxidative capacity; efficiency, gO\(_2\)/kW*h; average efficiency; gas to liquid ratio \( Q_g/Q_l \); the gas to liquid average ratio.

An evaluation of the various pneumohydraulic aeration mechanisms is made. The possibility of creating an energy efficient device on the two-phase flows mixing principle in a pneumohydraulic aerator is shown.

The oxygen saturation degree and the diffusion coefficient for the oxygen distribution in the structure using pneumohydraulic aeration is determined.
It is proposed a mechanism for an energy-saving aerating device, which eliminates mixing devices using an additional electric power, and applies the mechanism for obtaining a rotational motion only due to the hydro-aerodynamics of the jet itself according to the Segner's wheel principle.

The characteristics of the oxygen and active silt interaction are determined by the example of a model using sodium sulfite.

The multifunctional energy container [14] has a compact unit of treatment facilities (Fig. 3), using the described pneumatic-hydraulic rotating aerator.

![Figure 3. Compact unit of treatment facilities: 1 – percolator; 2 - settling trench; 3 - fermentation anaerobic zone; 4 – inert bacteria carrier; 5 - thin layer blocks; 6 – filter; 7 - airlift pump; 8 - pneumatic-hydraulic jet aerators; 9 - catalyst chamber; 10 - ultra-violet water treatment block; 11 – sediment; 12 - thermal insulation; 13 – aeration equipment block.](image)

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