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Determination of the Optimal Parameters of the Jet Aeration

To cite this article: M Radkevich *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **939** 012029

Determination of the Optimal Parameters of the Jet Aeration

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Abstract. To ensure effective aeration of the biological wastewater treatment process, easy-to-operate and not too energy-intensive units are needed. Jet aerators have such capabilities. In this study, the authors searched for the best hole shape for the aeration nozzles. It was determined that a nozzle with an elongated hole has the largest size of the actively aerated zone. Experimental studies of nozzles of a diameter of 56 mm with nozzles of elongated shape showed that the best characteristics of mass transfer are provided by nozzles with a total area of holes of 356 mm^2 at a flow rate of 10 ... 12 m/s. For practical calculations, an equation was obtained for the dependence of the oxygen transfer coefficient $K_{L\alpha(20)}$ on the complex criterion *vn*, and a method for calculating aeration units was developed, which is applicable for aerators with elongated holes.

1. Introduction

The problems of water resources, their rational use and protection from pollution are attracting the attention of scientists worldwide. Currently, a huge number of industries require biological wastewater treatment. The quality of biological treatment largely depends on the efficiency of the aeration process. In this regard, in many foreign countries, including Russia, India, Germany, the USA, etc., special attention is paid to the improvement of aeration systems.

The use of traditional methods of aeration is associated with a number of difficulties. For example, units with pneumatic mixing require expensive, labor-intensive compressor stations [1, 2].
When operating units with mechanical mixing, it is required to solve the issues of pressurization of equipment. Such units contain internal movable devices and a complex drive, which significantly reduces their operational reliability and maintainability [3, 4].
Units with combined (pneumo-mechanical) mixing occupy an intermediate position in terms of the efficiency of dissolving air oxygen and have a high degree of mixing; but the complexity of the design greatly reduces their advantages, since combined systems possess the disadvantages of pneumatic and mechanical apparatuses [5].
The search for ways to improve the technical characteristics of gas-liquid equipment led to the development of static devices for injection and dispersion of gas by liquid jets created by a remote-mount pump [6]. Apparatus with gas dispersion by liquid jets has recently found widespread use due to a number of advantages: a high rate of gas dissolution in a liquid, less energy consumption, and a simple design.
Of all the known methods, jet gas-liquid aeration is the most effective method for water oxygenation [7]. Apparatus with jet mixing have become widespread in biological wastewater treatment facilities (aeration tanks, oxidizing channels, ponds, etc.) [4, 7, 8, 9].
A limiting factor in the wide use of jet-type units is the imperfection of designs and the absence of a scientifically substantiated method for calculating the basic hydrodynamic and mass transfer characteristics. In this regard, there is a need for theoretical and experimental studies of aeration processes in these units.
The mechanism for saturating a liquid with oxygen in such units is based on the injection of air by a jet of falling liquid flowing out of the nozzle. The surface of the liquid jet after leaving the nozzle, moving in a gaseous medium, becomes non-smooth, "rough". The gas penetrates into the depressions of the "roughness" and is carried away in the wake flow by the jet. At the point of impact of the jet against the liquid mirror, cavities and an air film are formed, which are "trapped" by the jet of liquid and the walls of the cavity. Further, the jet penetrates deep into the reaction volume, where the gas is dispersed in the form of small bubbles, forming a gas-liquid mixture with a complex interface in the contact zone [10, 11, 12, 13, 4, 14].
The sizes of the actively aerated zone can be increased by changing the depth of the reservoir, as was stated in [15].
Analysis of the literature sources on the injection ability of liquid jets shows that most authors associate the consumption of entrained gas Vr with the degree of turbulence of the jet, with the size of the `roughness' on the jet surface.

According to some researchers [4, 11, 16, 17, 18, 19, 20, 21], the main factor influencing the intensity of the turbulence of the jet is the shape of the nozzle.

Experiments conducted by E.V. Safronova, F. Meshcheryakov et al. [11, 9] showed that with an increase in the ratio of the nozzle perimeter to its cross section, the mass transfer coefficient KLα grows, all other things being equal; for example, the rectangular section of the nozzle is more appropriate than a circular cross-section.

Numerous literature data [22, 23, 24, 25, 2, 26], as well as observations conducted by the authors, have shown that in a gas-saturated volume of liquid, it is possible to distinguish the so-called actively aerated zone, permeated with gas bubbles, and the surrounding homogeneous zone.

The aim of this study was to find the optimal parameters of the nozzle for jet aeration from the point of view of the best indices of mass transfer and the size of the actively aerated zone.

2. Materials and methods

In experimental studies, we had to solve the following problems: to determine the most effective shape of the nozzle holes, and for the holes of this shape to determine their optimal sizes that provide the best indices of the aeration process.

2.1 Preliminary experiments

Preliminary experiments were conducted to compare the sizes of the actively aerated area for nozzles with round, elongated, rhomboid, and S-shaped holes (Figure 1). The nozzles were made of metal, the hole area was the same, 80 mm^2.

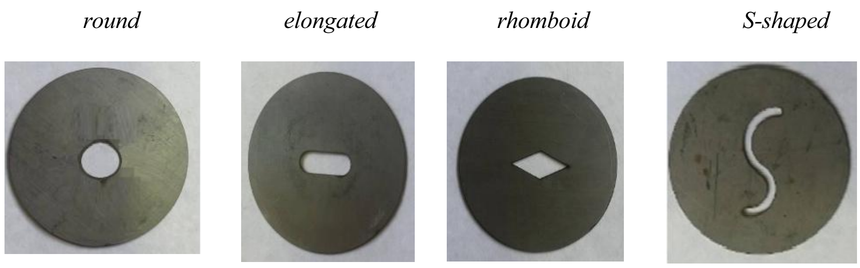

Figure 1. Photos of nozzles with different hole shapes for preliminary experiments

An experimental setup was made to conduct preliminary experiments (Figure 2). The setup consists of glass container 1 with dimensions 1x1 m in plan and a depth of 2 m, centrifugal pump 2, pipeline 3 for fluid circulation, replaceable hose 4 for adjusting the position of the nozzle, replaceable nozzles 5. The required liquid flow rate in the nozzles was set using valve 6. Sizes of the actively aerated zone (the depth of immersion of the jet H_{im} and the diameter of the jet flame d_f) were recorded using camera 7.

The water flow rate of a jet of aerating liquid fed was Q = 0.25 l/s.

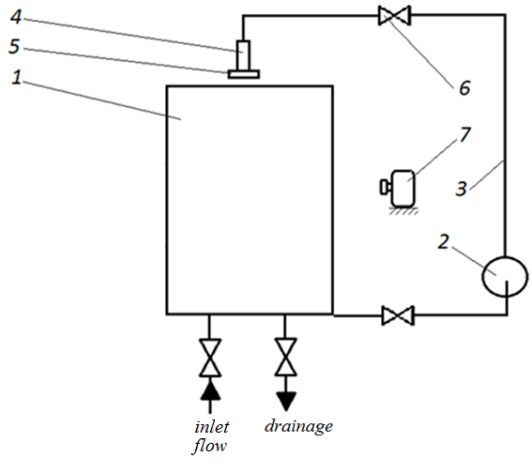

Figure 2. Scheme of the experimental setup

The experiments were performed in triplicate.

2.2 Experimental procedure for determining the characteristics of mass transfer for a nozzle with elongated holes

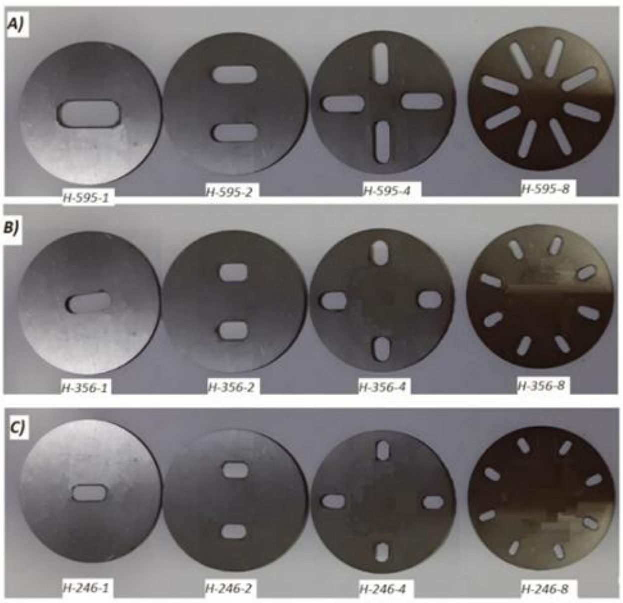

Figure 3. Photos of the sets of nozzles: A) with a hole area of 595 mm^2, B) with a hole area of 356 mm^2, C) with a hole area of 246 mm^2

After conducting a preliminary experiment, it was decided to investigate the jets formed in the nozzles with elongated holes in the form of a keyhole slot. It was assumed that the degree of turbulence would depend on the size and number of holes in the nozzle. It was required to determine the depth of immersion of the jet, the diameter of the gas-liquid jet of flame, and the concentration of dissolved oxygen.

The same experimental setup was used for this experiment (Figure 2), and the replaceable nozzles. The first set of nozzles has a total hole area of 595 mm^2, the second set - 356 mm^2, the third set - 246 mm^2. The area was provided with a different number of holes: 1, 2, 4, 8 (Figure 3). The diameter of the nozzle was 56 mm.

The depth of immersion of gas bubbles H_{np} and the diameter of the gas-liquid jet flame – of the cone d_f were recorded using a Canon EOS M6 Mark II camera with a shooting rate of 14 frames per second.

The concentration of oxygen dissolved in water was measured by the HORIBA U-50 electrochemical analyzer, equipped with a remote-mount sensor, which allows taking readings at any point in the aeration tank. The device can measure not only the oxygen content in water but also its temperature and pH.

Determination of the immersion depth H_{im} and the concentration of dissolved oxygen was performed for models of each type in 3 replicates at water flow rates Q = 1, 2, 3, 4, 5 l/s.

The experiments were conducted under standard conditions, that is, with completely deoxygenated water and normal pressure.

2.3 Calculated determination of mass transfer characteristics

The following formulas were used [27, 28, 2, 29] to determine the characteristics of mass transfer.

Jet flow rate

$$V=Q/S\,, \tag{1}$$

where Q is the water flow rate, m^3/s; S is the cross-sectional area of the jet, m^2.

Power

$$P=1/2\,\rho\,Q\cdot V^2, \quad \text{kW} \tag{2}$$

where ρ is the density of the liquid, kg/m^3

Oxygen volumetric transfer coefficient

$$K_{L\alpha t}=\frac{1}{t}\ln\left(\frac{c_s-c_0}{c_s-c_t}\right),\ 1/s \tag{3}$$

t – is the time, s (the duration of each experiment was t = 60 s); C_s is the concentration of O_2 saturation at a given temperature; C_0 is the concentration of O_2 at the beginning of the experiment (C_0 = 0); C_t is the concentration of O_2 at the end of the experiment

Standard oxygen transfer coefficient (at t = 20°C)

$$K_{L\alpha(20)} = K_{L\alpha t} \cdot \theta^{(20-T)}, \text{ 1/s} \quad (4)$$

θ=1,024 at T=5…24°C; θ=1,028 at T=25…34°C; θ=1,036 at T=35…45°C

Oxygen transfer rate is

$$O_R = K_{La(20)} \cdot 3600 \cdot C_s \text{ , mg/(l/h)} \quad (5)$$

Oxygen transfer efficiency is

$$E = O_R \cdot W/P \text{ , kgO}_2\text{/kW·h} \quad (6)$$

W is the volume of water in the tank, m^3.

3. Results and Discussion

The results of preliminary experiments on the choice of the best shape of the nozzle hole according to the criterion "size of the actively aerated zone" are given in Table 1.

Table 1. Results of experiments on preliminary assessment of the size of an actively aerated zone

Hole type of the nozzle	round	elongated	rhomboid	S-shaped
Area S, mm^2			80	
Water flow rate Q, l/s			0.25	
Immersion depth H_{im}, mm	62	118	59	52
Jet flame diameter d_f, mm	25	47	24	21

Based on the results of the preliminary experiment, it was found that the greatest size of the actively aerated zone can be obtained using nozzles with elongated holes.

Table 2. Results of an experiment to determine the characteristics of mass transfer

Model	Expe-ri-ment No.	Velocity, m/s	Num-ber of holes	Peri-meter, mm	$K_{La(20)}$ (x 10^{-2} s^{-1})	O_2 transfer efficiency, kgO_2/(kW·h)	Immer-sion depth, H_{im}
H-246	1	4.507	1	67.143	0.06	14.640	39.0
	2	8.510		67.143	0.13	4.788	50.5
	3	12,026		67.143	0.25	2.607	57.5
	4	15.538		67.143	0.34	1.661	64.0
	5	19.054		67.143	0.45	1.161	69.5
	6	4.507	2	47.143	0.05	12.223	39.0
	7	8.510		47.143	0.11	3.998	49.0
	8	12.026		47,143	0.23	2.176	56.5
	9	15.538		47.143	0.40	1.387	62.5
	10	19.054		47.143	0.52	0.969	68.0
	11	4.507	4	33.571	0.04	9.338	37.5
	12	8.510		33.571	0.09	3.054	48.5
	13	12.026		33.571	0.22	1.663	55.5
	14	15,538		33.571	0.47	1.060	61.5
	15	19.054		33.571	0.62	0.740	67.0
	16	4.507	8	23.571	0.02	8.231	37.0
	17	8.510		23.571	0.07	1.692	47.5
	18	12.026		23.571	0.21	1.466	54.5
	19	15.538		23.571	0.40	0.934	60.5
	20	19.054		23.571	0.78	0.653	65.5
H-356	*21*	2.438	1	80.714	0.71	17.846	32.5
	22	5.673		80.714	0.97	5.836	45.5
	23	8.017		80.714	1.30	3.177	55.5
	24	10.359		80.714	1.44	2.025	58.0
	25	12.703		80.714	1.80	1.415	63.0
	26	2.438	2	57.143	0.63	14.601	32.0
	27	5.673		57.143	0.87	4.775	45,0
	28	8.017		57.143	1.38	2.600	51.5
	29	10.359		57.143	1.58	1.657	57.0

	30	12.703		57.143	2.12	1.157	62,0
	31	2.438	4	40.714	0.52	11.761	31.5
	32	5.673		40.714	0.80	3.846	44.0
	33	8.017		40.714	1.50	2.094	51.0
	34	10.359		40.714	2.41	1.335	56.0
	35	12.703		40.714	2.97	0.932	61.0

Continuation of Table 2

H-356	36	2.438	8	28.571	0.29	9.832	31.0
	37	5.673		28.571	0.68	3.216	43.0
	38	8.017		28.571	1.61	1.751	50.0
	39	10.359		28.571	2.62	1.116	55.0
	40	12.703		28.571	3.33	0.779	60.0
H-595	41	1.870	1	104.244	0.21	23.371	32.0
	42	3.520		104.244	0.38	7.644	41.5
	43	4.978		104.244	0.58	4.161	47.5
	44	6.443		104.244	0.80	2.652	52.5
	45	7.901		104.244	1.07	1.853	57.0
	46	1.870	2	73.542	0.16	19.288	31.5
	47	3.520		73.542	0.33	6.308	40.5
	48	4.978		73.542	0.75	3.434	46.5
	49	6443		73.542	1.26	2.189	51.5
	50	7.901		73.542	1.33	1.529	56.0
	51	1.870	4	52.122	0.13	15.738	31.0
	52	3.520		52.122	0.29	5.147	40.0
	53	4.978		52.122	0.71	2.802	46.0
	54	6.443		52.122	1.42	1.786	51.0
	55	7.901		52.122	1.55	1.248	55.0
	56	1.870	8	37.128	0.09	12.684	30.5
	57	3.520		37.128	0.21	4.148	39.0
	58	4.978		37.128	0.66	2.258	45.0
	59	6.443		37.128	1.60	4.439	50.0
	60	7.901		37.128	2.00	1.006	54.5

Therefore, subsequent experiments to determine the characteristics of mass transfer and the size of the actively aerated zone were conducted for nozzles with elongated holes of various sizes. The jet immersion depth and oxygen concentration during aeration were measured directly during the experiments, and the velocity, standard oxygen transfer coefficient, and oxygen transfer efficiency were calculated using formulas (1) - (6). The results of the experimental and calculated values are shown in Table 2.

Based on the results of the experiment, the aeration process was optimized. As an optimization parameter to obtain the maximum possible sizes of the actively aerated zone, the jet immersion depth H_{opt} = 62±7 cm was chosen as the deepest one obtained in the experiments. From the entire array of experimental data for optimization, only data with the immersion depth within the specified intervals were selected (see Table 2 for the numbers of experiments 3, 4, 5, 8, 9, 10, 13, 14, 15, 18, 19, 20 for nozzles of the H-246 group; for numbers 24, 25, 29, 30, 34, 35, 39, 40 for nozzles of the H-356 group and for numbers 45, 50, 55, 60 for nozzles of the H-595 group). Plotting H_{opt} as a certain horizontal axis, on which the numbers of experiments are marked, vertical lines are drawn through each number of experiments. The calculated values of the standard oxygen transfer coefficient $K_{L\alpha(20)}\cdot 10^{-2}$ are marked upward along these vertical lines; and the aeration efficiency E, kgO_2/kWh is marked downward along this line. Thus, a pattern of the ongoing processes was obtained (Figure 4), from which it is obvious that the aeration process obtained with nozzles of the H-356 group (the highest $K_{L\alpha(20)}$ and an acceptable aeration efficiency) can be considered optimal. The shaded area in the graph in Figure 4 shows the zone of the optimal combination of the indices obtained.

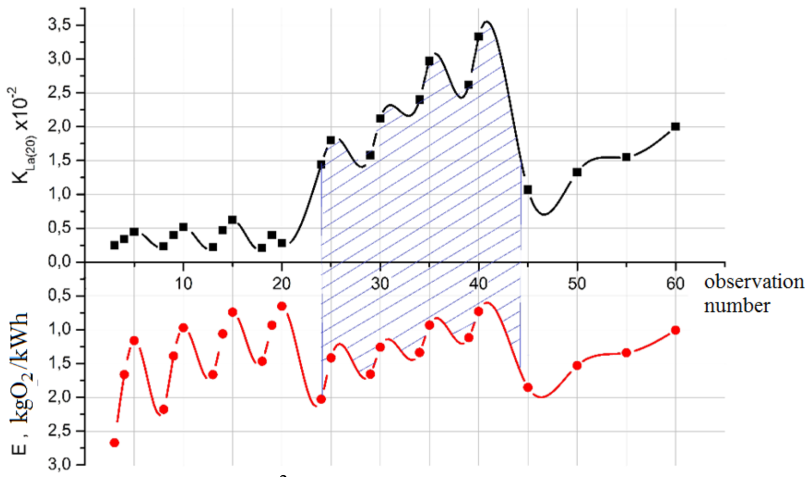

Figure 4. Values of $K_{L\alpha(20)}\cdot 10^{-2}$ and aeration efficiency for H_{opt} = 62 ± 7 cm

The results of the performed optimization show that for practical use it is appropriate to use an aerator with nozzles of the H-356 type. The authors have developed a method for calculating an aerator of the H-356 type, based on the selection of the oxygen transfer coefficient and its comparison with the required one under the conditions for reducing the waste liquid to the required BOD value. Since for calculating the aeration unit, it is necessary to be able to choose $K_{L\alpha(20)}$ depending on the jet velocity v and the number of holes n in the nozzle, let us consider the dependence of $K_{L\alpha(20)}$ on the product $v \cdot n$ in the array of experiment numbers 24, 25, 29, 30, 34, 35, 39, 40.

For the convenience of calculation, a sample of the results that fall into the optimum zone is made from Table 2 and is summarized in Table 3.

Table 3. Optimal indices of the aeration process

Velocity v, m/s	Number of holes	$K_{La(20)}$ (x 10^{-2} s^{-1})	O_2 transfer efficiency, kgO_2/(kW·h)	Immersion depth H_{im}
10.359	1	1.3	3.177	55.5
12.703	1	1.44	2.025	58
10.359	2	1.58	1.657	57
12.703	2	2.12	1.157	62
10.359	4	2.41	1.335	56
12.703	4	2.97	0.932	61
10.359	8	2.62	1.116	55
12.703	8	3.33	0.779	60

According to the data given in Table 3, a graph of dependence of $K_{L\alpha(20)}$ on the product $v \cdot n$ is plotted. The processing of experimental data in the *Origin* environment showed that a polynomial of the 4th degree gives the highest convergence with the experimental graph:

$$Y = A + B_1 \cdot X + B_2 \cdot X^2 + B_3 \cdot X^3 + B_4 \cdot X^4 \quad (7)$$

For this polynomial, the values of the coefficients were obtained (Table 4) and the statistics of the model reliability was calculated (Table 5).

Table 4. The values of the coefficients of the mathematical model

Coefficient	Value	Error
A	2.02308	0.89445
B1	-0.08544	0.10392
B2	0.00494	0.00361
B3	-7.705E^{-5}	4.77096E^{-5}
B4	3.73021E^{-7}	2.1161E^{-7}

Table 5. Model reliability statistics $K_{L\alpha(20)} - vn$

Index	Coefficient of determination	Standard deviation	p-value
Value	0.93881	0.25387	0.03645

As a result, the following equation was obtained to describe the dependence $K_{L\alpha(20)} - vn$.

$$K_{L\alpha(20)} = (2{,}02308 - 0{,}08544\cdot(vn) + 0{,}00494\cdot(vn)^2 - 7{,}705\cdot10^{-5}\cdot(vn)^3 + 3{,}73\cdot10^{-7}\cdot(vn)^4)\cdot10^{-2} \quad (8)$$

The experimental and theoretical graphs of the $K_{L\alpha(20)} - vn$ dependence are shown in Figure 5.

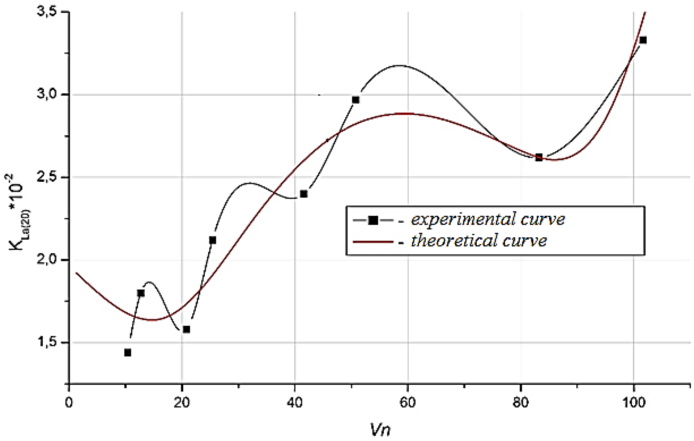

Figure 5. Experimental and theoretical graphs of the dependence of $K_{L\alpha(20)}$ on the jet velocity *v* and the number of holes *n*

Table 6 shows a comparison of the $K_{L\alpha(20)}$ values, obtained from the results of the experiment and calculated by the model (8). The deviations are within ± 12%, which is acceptable for practical calculations [30].
Having selected $K_{L\alpha(20}$ according to the selected values of v and n, we determine the required $K_{L\alpha(20}$ according to the condition of the BOD decrease by the following formula [31]:

$$K^{req}_{L\alpha(20)} = \frac{z(L_0 - L_t)\times Q_{ww}}{(C_{sol} - C)\times W} \quad (9)$$

where *z* is the specific consumption of O_2 of the removed BOD_{total}, mg/mg, z = 1.25 [32]; L_0 – is the BOD of the inlet fluid, L_t is the required BOD; Q_{ww} – is the waste liquid rate, m^3/day; C_p – is O_2 solubility in water (C_p = 9.1 mg/l at 20°C [33]), *C* is the average concentration of O_2 in the structure (*C* = 2 mg/l), *W* is the structure volume, m^3.

The required $K_{L\alpha(20)}^{\text{req}}$ is compared with the $K_{L\alpha(20)}$, provided by the designed aerator. If the condition $K_{L\alpha(20)}^{\text{req}} \leq K_{L\alpha(20)}$ is met, a conclusion is made on the suitability of the designed aerator.

Table 6. Table of prediction and deviation for polynomial regression analysis of standard oxygen transfer coefficient

No.	Experiment $K_{L\alpha(20)}$	Theoretically predicted	Deviation, l/s	Deviation, %
1	1.44	1.586507	-0.14651	-10.1741
2	1.8	1.586641	0.213359	11.8533
3	1.58	1.759625	-0.17962	-11.3686
4	2.12	1.932634	0.187366	8.83801
5	2.4	2.58795	-0,.8795	-7.83127
6	2.97	2.814312	0.155688	5.242008
7	2.62	2.609102	0.010898	0.415966
8	3.33	3.275276	0.054724	1.64335

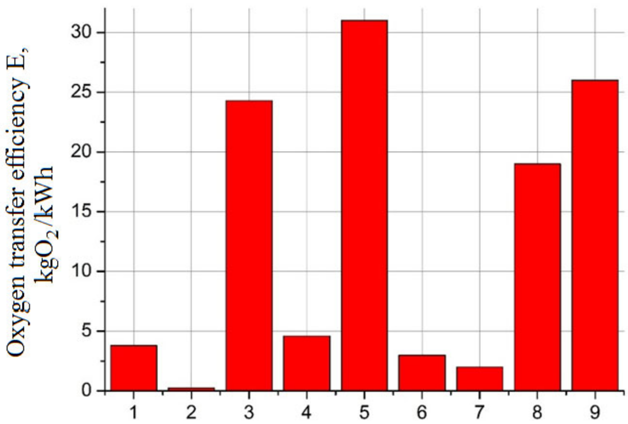

Figure 6. Histogram comparing the value of E according to the results of different studies: 1 - K. Tojo and Miyanami - ascending and descending flows in gas-liquid mixers [8]; 2 – N. Kulya - submerged jet aerators with different nozzle heights [34]; 3 - S. Deswal - submerged nozzles with different number of round holes [35]; 4 - A. Bin - high-velocity jets with a large diameter [36]; 5 - S.Singh - nozzles with different geometries, incl. rectangular and rectangular with rounding [21], 6 - E. Dmukhaylo - vertical pipes with ejector nozzles [37]; 7 - V. Pomogaeva - freely falling jets of circular cross section [29]; 8 - A. Ahmed - submerged round jets of low velocity [38]; 9 – the results of current research

The results of this study are comparable to the results obtained by other researchers.
Comparative results of various researchers on the oxygen transfer efficiency are presented in the form of a histogram (Figure 6).
Figure 6 shows that the results obtained in this study (model H-356-1) are better than the ones obtained in most studies and are quite close to the results obtained by Singh [21]. As a rule, in jet aeration, the value E = 2 ... 4.6 kgO_2/kW-h is reached [36]. Based on the above comparison, it was concluded that the aerator with a “keyhole slot” nozzle is the most effective.

4. Conclusions

The results of the studies have shown that in jet aeration, nozzles with elongated holes surpass other types of holes in their ability to create an actively aerated zone of maximum size.
Comparison of nozzles with elongated holes of different areas allows us to conclude that the optimal sizes of the aeration zone create nozzles of the H-356 group with the highest oxygen transfer coefficient $K_{L\alpha(20)}$ and acceptable aeration efficiency. The mathematical description of the dependence of $K_{L\alpha(20)}$ on the product $v \cdot n$ obtained for the zone of optimal values of these indices allows conducting a simple calculation of the jet aerator, which can help accelerate the design processes of small treatment facilities.
Despite the good indices of mass transfer, the proposed method of jet aeration can be used for biological wastewater treatment only in shallow tanks since the depth of immersion of the jet is relatively small. Thus, the results of the study can be used in the design of biological treatment facilities for relatively small enterprises, many of which in the territory of the Republic of Uzbekistan discharge wastewater directly into water bodies.

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