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Increasing the Oxygen Transfer Rate to Stationary Water

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Abstract: *The paper analyzes the equation of the oxygen transfer rate to water; the factors that lead to the increase of this speed are specified.*
Further, a single factor is studied, namely "shrinking the orifice diameter" in the perforated plate of a fine bubble generator.
Two versions are studied:
- version I: the perforated plate has orifices with a diameter of 0.1 mm;
- version II: the perforated plate has orifices with a diameter of 0.05 mm.
The constructive solutions for the two versions are presented and the methodology of experimental researches is exposed.
The experimental results obtained regarding the increase of the concentration of dissolved oxygen in water, as a function of time, reveal that version II is more favorable here.

Keywords: *Water aeration; fine bubble generators; oxygen transfer rate.*

1. Introduction

Aeration plants aim to increase the content of dissolved oxygen in water, this increase ensuring a favorable development of all forms of life in water.
Water aeration can be achieved as follows [1] [2]:
- by mechanical aeration;
- by pneumatic aeration;
- by mixed aeration.

The most effective is pneumatic aeration and it consists in the introduction of air bubbles into the water.
Water can be stationary (in pools) or moving (flowing through pipes) [3-5].
Pneumatic aeration includes:
A) Aeration installations constructed of pipes with orifices;
B) Aeration installations with porous diffusers;
C) Aeration systems with bubble generators.
Bubble generator aeration systems include [6]:
a) Aeration equipment's producing nanobubbles (Ø <100 nm);
b) Aeration equipment's producing fine bubbles (Ø <1mm);
c) Aeration equipment's producing medium bubbles (Ø <1 - 3 mm);
d) Aeration equipment's producing large bubbles (Ø <3 - 120 mm).
To obtain fine bubbles, the diameter of the orifice must be as small as possible (d_0 <1 mm) and the distribution of the orifices in the plate must be uniform.
These two conditions can be achieved with the help of advanced micro-processing technologies [7] [8]:
• spark erosion processing;
• electrochemical processing;
• laser processing;
• electron beam processing;
• machining with micro-drilling machines in coordinates, with drills of Ø <0.5 mm.
Any of the above technologies must solve the problem of machining precision of the parts.

The processing precision means the extent to which the conditions provided in the execution drawing of the part have been ensured; these conditions refer to the shape of the part, the dimensional accuracy, the reciprocal positions of the surfaces and the quality of the surface [7] [8]. The permissible deviations are also indicated under the conditions provided in the drawing; it indicates the proximity degree required by processing for size, shape, etc., to an optimal constructive solution of the respective part [9].

2. Materials and methods

2.1 Materials

Paragraph: In the first version, a fixed fine bubbles generator is used for aeration of stationary water; it emits air bubbles in the water through a plate with orifices Ø 0.1 mm (figure 1). The plate thickness s = 2 mm, has 113 orifices with a diameter of d_0 = 0.1 mm, and the distance between the orifices is d = 2 mm. Thus, the two conditions were met [10]:

$$\frac{s}{d_0} > 3 \rightarrow \frac{2}{0.1} = 20 \tag{1}$$

$$\frac{d}{d_0} > 3 \rightarrow \frac{2}{0.1} = 20 \tag{2}$$

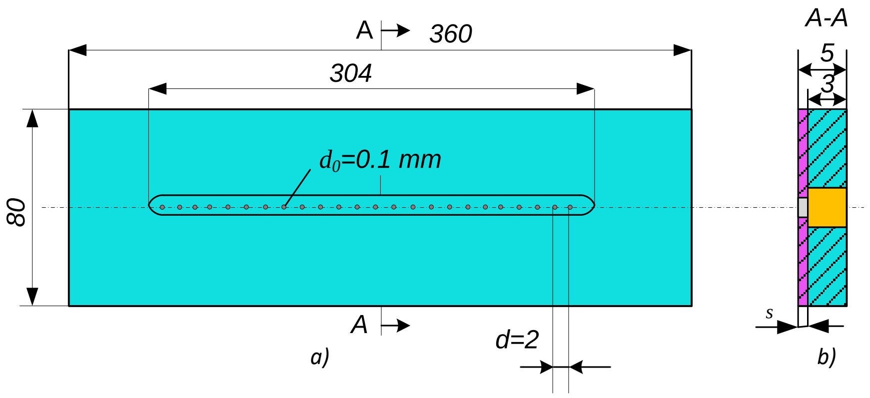

Fig. 1. Plate with orifices with a diameter of 0.1 mm
a) plane view; b) cross section.

In figure 2, one can observe the constructive solution of the fine bubble generator for version I:

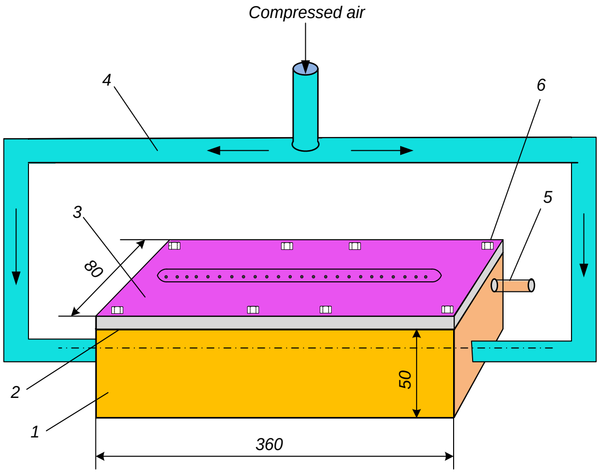

Fig. 2. Fine air bubble generator
1-compressed air tank; 2- sealing gasket; 3- plate with orifices Ø 0.1 mm;
4- G.B.F compressed air supply pipe; 5-connection for measuring the compressed air pressure; 6- screws for fixing the tank plate.

To perform the orifices of Ø 0.1 mm in the plate, a channel was created with a depth of 3 mm and a length of 304 mm; the orifices through which the air comes out has a thickness of 2 mm. Subsequently, with the help of a special machine used for micro processing, KERN Micro type, the 113 orifices with Ø 0.1 mm were made in the channel.
Figure 3 shows the scheme of the installation for version I; for the compressed air entering the fine bubbles generator, the pressure is measured with a digital manometer, the temperature with a digital display thermometer and the flow rate with a rotameter.

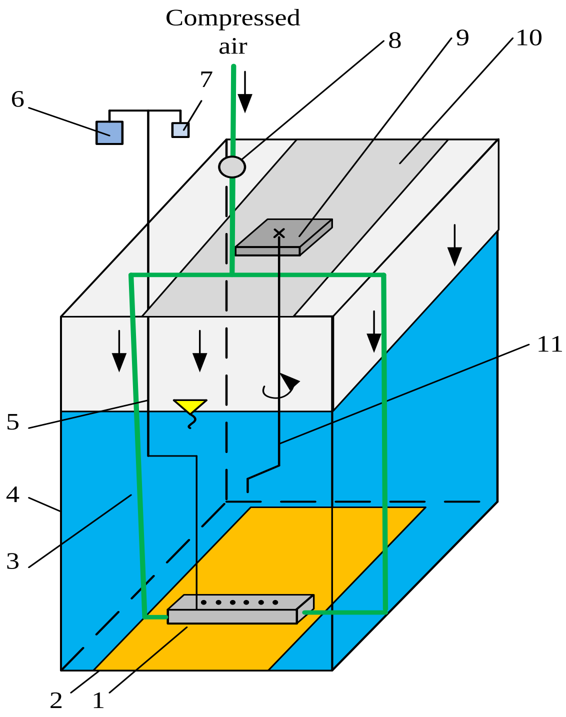

Fig. 3. The location of a FBG in the water tank
1-FBG; 2- the FBG support platform; 3- compressed air pipe; 4- water tank; 5- connection for measuring the pressure and temperature of the air in the FBG body; 6- digital device for pressure measuring; 7- digital device for temperature measuring; 8- rotameter; 9- mechanism of actuation of the oxygenometer probe; 10- support platform; 11- oxygenometer probe.

Figure 4 shows the fine bubbles generator in function.

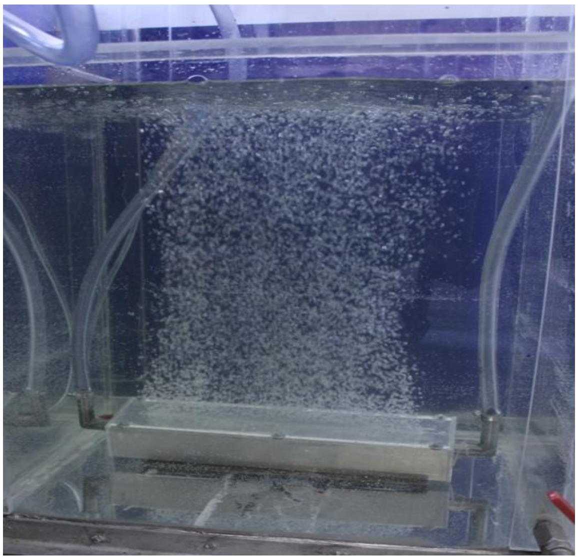

Fig. 4. FBG with orifices Ø 0.1 mm, in operation.

In version I, the area of the air-to-water outlet section will be:

$$A_I = n_I \cdot \frac{\pi}{4} \cdot d_I^2 = 113 \cdot \frac{\pi}{4} \cdot (0.1 \cdot 10^{-6})^2 = 0.887 \cdot 10^{-6} m^2 \tag{3}$$

To make a comparison between the two versions, the area of the air outlet section in the water will have to be the same ($A_I = A_{II}$) [11].
In version II, in which the orifices have Ø 0.05 mm, the number of orifices will be four times higher, i.e., 452 orifices.

$$\frac{A_I}{A_{II}} = \frac{n_I \cdot \frac{\pi}{4} \cdot d_I^2}{n_{II} \cdot \frac{\pi}{4} \cdot d_{II}^2} = \frac{113 \cdot 0.1^2}{4 \cdot 113 \cdot 0.05^2} = 1 \tag{4}$$

The total number of orifices (452) is divided into 4 circular plates, each containing 113 orifices with Ø 0.05 mm. Each plate has a thickness s = 2 mm; the location of the orifices complies with the conditions:

$$\frac{s}{d_0} > 3; \frac{d}{d_0} > 8 \tag{5}$$

Horizontally, the distance between two orifices on the same line is 10 mm and d_0 = 0.05 mm. The conditions become:

$$\frac{s}{d_0} = \frac{2}{0.05} = 40 > 3; \frac{d}{d_0} = \frac{10}{0.05} = 200 > 8 \tag{6}$$

In the vertical direction, the distance between two orifices is also 10 mm. In the oblique direction (the line AB in figure 5) one can obtain:

$$\frac{d}{d_0} = \frac{\sqrt{5^2 + 5^2}}{0.05} = 141.4 > 8 \tag{7}$$

Figure 5 shows the orifices plate, made of transparent plexiglass; the plate is mounted on a cylinder with an outer diameter of 105 mm.

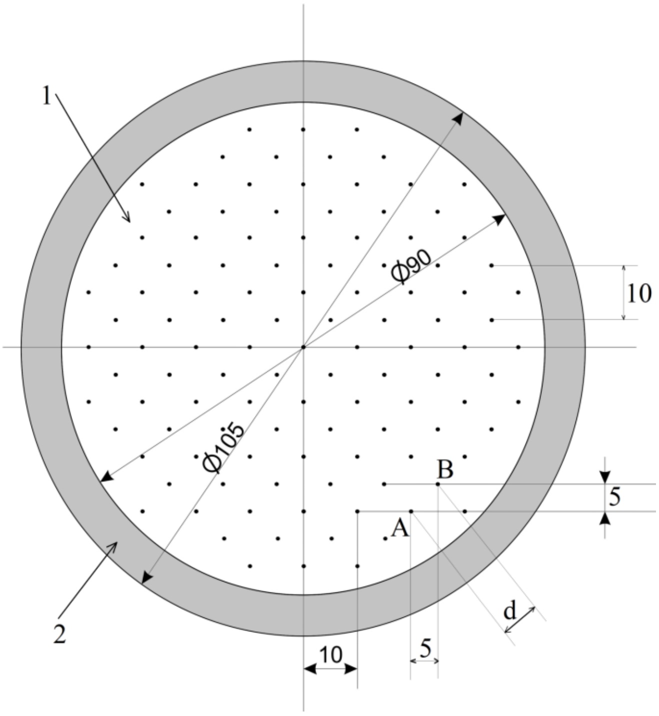

Fig. 5. The orifice plate: n = 113; Ø 0.05 mm
1 - plate with orifices; 2- frame for fixing the plate.

Figure 6 shows the scheme of the experimental installation, designed for the second version (set of four microbubble generators). The compressed air supplied by the electrocompressor (2) passes through the pressure reducer (4) to the four-cylinder assembly (7); the compressed air pressure must overcome the hydrostatic load (H), i.e., the height of the water layer in the tank (8) and the loss of air pressure when passing through the orifices.

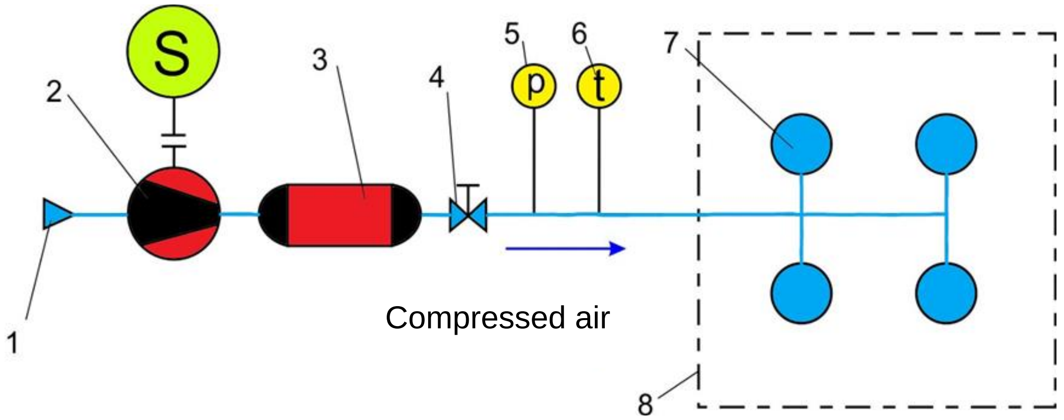

Fig. 6. The scheme of the experimental installation for water aeration using fine bubble generators.
1 - air filter; 2 - electrocompressor; 3 - compressed air tank; 4 - pressure reducer; 5 - pressure measuring device; 6 - temperature measuring device; 7 - set of four cylinders each supporting a plate with orifices of Ø = 0.05 mm; 8 - water tank.

In version II, atmospheric air (21% O_2 and 79% N_2) is introduced into the water tank by means of the fine bubble generator which has 4 cylinders, each cylinder having a perforated plate with 113 orifices Ø 0.05 mm (figure 7).
Figure 7 shows a side image of the fine bubble generator with plates with orifices Ø = 0.05 mm. In the second version, the 4 cylinders with the perforated plate at the top can be seen.

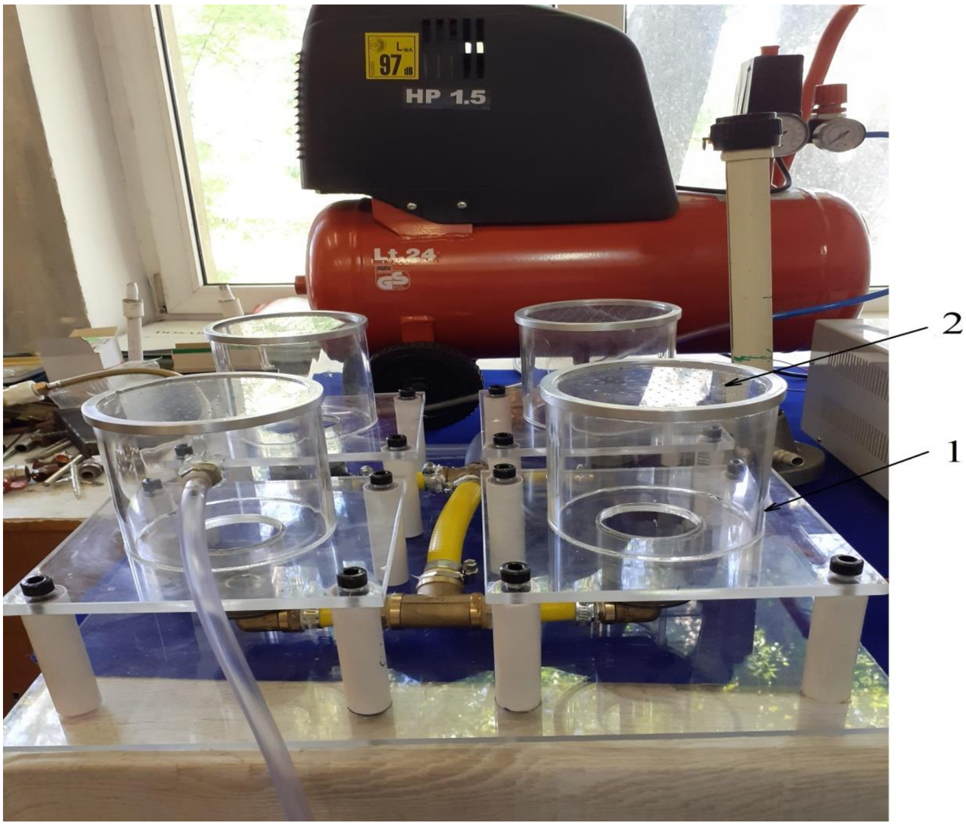

Fig. 7. Side view of the fine bubble generator
1 - cylinder with Ø = 105 mm; 2- perforated plate with Ø = 90 mm.

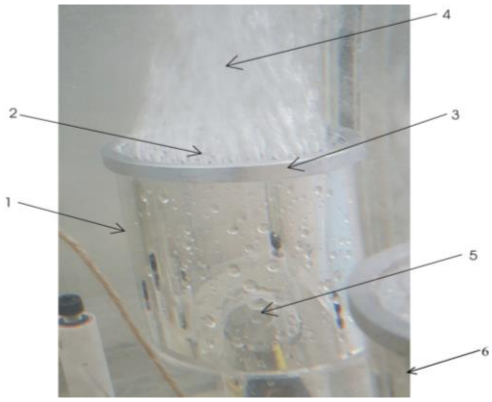

Fig. 8. One FBG element with Ø 0.05 mm in operation
1 - cylinder body; 2 - plate with 113 orifices Ø 0.05 mm; 3 - clamping ring; 4 - bubble column; 5 - compressed air connection; 6 - water tank.

The operation of a component (one cylinder) of the fine bubble generator is shown in figure 8.

2.2. Methods

The rate of oxygen transfer to water is specified by the relation [2] [12]:

$$\frac{\mathrm{d}C}{\mathrm{d}\tau} = a \cdot k_L \left(C_s - C\right) \tag{8}$$

where:
C –the concentration of dissolved oxygen at time τ;
a · k_L –the volumetric mass transfer coefficient;
C_s – the oxygen concentration in water, at saturation.

$$a = \frac{A}{V}\left[\frac{m^2}{m^3}\right] \tag{9}$$

where:
a – the specific interfacial area between air and water;
A – the area of gas bubbles [m^2];
V– the volume of the biphasic system (air + water) [m^3];
k_L – the mass transfer coefficient [m / s].
Relation (8) indicates the change of the oxygen concentration in time, because of the molecular diffusion of oxygen from the area with high concentrations to the area with low concentrations.
Analyzing the relation (1) one can observe a series of factors that influence the change in the rate of oxygen transfer to water; these factors are presented in table 1.

Table 1: Solutions for increasing dC/dτ.

No.	The pursued goal	The theoretical solution	The practical solution
1	The increase of C_s	Increasing the O_2 concentration in the air introduced into the water.	Introduction of oxygen, ozone (O_3) into water
2	The decrease of C_0	Minimum values for C_0 depending on the nature of the micro-organisms present in the water	Decreased initial water temperature; Introduction of C_0-reducing substances into water.
3	The increase of k_L	Intensification of turbulence	FBG rotation Using mobile FBG
4	The increase of a	Decrease the gas bubble diameter	Decreasing of the FBG orifices diameter.

From table 1 it results that, to increase the concentration of dissolved oxygen in water, it is necessary to reduce the diameter of the orifices of the fine bubble generators, therefore, implicitly to decrease the diameter of the air bubbles immersed in water [13].

As a result, the use of micro technologies in water aeration processes is considered for creating aeration installations that produce air bubbles with a diameter of less than 1 mm.
For a sphere of radius "r" and diameter "d", the relation (9) becomes:

$$a = \frac{A}{V} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3r^3}{r^3} = \frac{3}{\frac{d}{2}} = \frac{6}{d} \qquad (10)$$

From relation (10) one can observe that for a spherical air bubble “a” it will increase if the diameter of the air bubble will decrease. The diameter of the air bubble is proportional to the diameter of the air bubble outlet in the water.
The paper studies two versions:
-Version I: FBG has a plate with orifices with a diameter d_I = 0.1 mm
-Version II: FBG has a plate with orifices with a diameter d_{II} = 0.05 mm
The relation (10) for the two versions becomes:

$$a_I = \frac{6}{d_I} = \frac{6}{0.1} = 60 \qquad (11)$$

$$a_{II} = \frac{6}{d_{II}} = \frac{6}{0.05} = 120 \qquad (12)$$

Because a_{II} is higher than a_I it is predicted that the oxygen transfer rate to water will be higher in the case of version II [14].

3. Results and discussion

3.1. Results

As initial data, at the beginning of the experimental measurements there are specified:
- The volume of water in the tank: V_{H2O} = 0.125 m^3;
- The height of the water layer in the tank: H = 0.5 m;
- The initial concentration of the dissolved oxygen in water: C_0 = 5.84 mg / dm^3;
- The water temperature;

Because the experimental measurements were performed on different days, the water temperature was different, as follows:
- for version I: t_{H2O} = 23.7 °C, which corresponds to a concentration of dissolved oxygen at saturation f C_s = 8.4 mg / dm^3 [1];
- for variant II: t_{H2O} = 19.5 °C, which corresponds to a concentration of dissolved oxygen at saturation C_s = 9.2 mg / dm^3;

e) The air flow rate introduced into water: $\dot{V}$= 0.6 m^3 / h;
f) The air pressure, measured in the body of the fine bubble generator: p = 583 mmH$_2$O
g) The duration of the experiments: τ = 120 min.
The results of the experimental measurements are presented in Tables 2 and 3:

Table 2: Experimental data for version I: C = f (τ).

No.	τ [min]	0	15	30	45	60	75	90	105	120
1	*C* [mg/dm^3]	5.89	6.89	7.65	8.01	8.10	8.26	8.31	8,.35	8.39
2	*Cs* [mg/dm^3]	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4

Table 3: Experimental data for version II: C = f (τ).

No.	τ [min]	0	15	30	45	60	75	90	105	120
1	*C* [mg/dm^3]	5.84	7.90	8.20	8.35	8.53	8.71	8.75	8.85	9.00
2	*Cs* [mg/dm^3]	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2

The results presented in Tables 2 and 3 fall within the range of values obtained in other specialized papers [15-19].

3.2. Discussion

The aim of experimental researches is to evaluate the variation of the concentration of dissolved oxygen in water, as a function of time: C = f (τ).
Performing the measurements involves the following steps:
1. Check that the 113 orifices with Ø = 0.1 mm function, i.e., the atmospheric air is introduced into the bubble generator;
2. Fill the tank with water up to H = 500 mm H_2O;
3. Measure C_0, t_{H2O}, t_{air};
4. Insert the fine bubble generator into the water tank and note the time (τ);
5. Every 15 minutes, take the fine bubble generator out of the tank and measure the dissolved oxygen concentration; subsequently, reinsert the fine bubbles generator in the water tank.
6. When a horizontal level of the function C = f (τ) is reached, the measurements stop, with the condition: C ≈ Cs;
7. From previous researches [20-21], the concentration of dissolved oxygen in water tends to saturate after two hours. Therefore, the measurement of the oxygen concentration will be performed at the moments: 15, 30, 45, 60, 75, 90, 105, 120 minutes.
8. At the end of the measurements, clean the oxygenometer probe and drain the water from the tank. Figure 9 shows that the values of the dissolved oxygen concentration in water are higher in version II, red curve, than those of version I, blue curve.

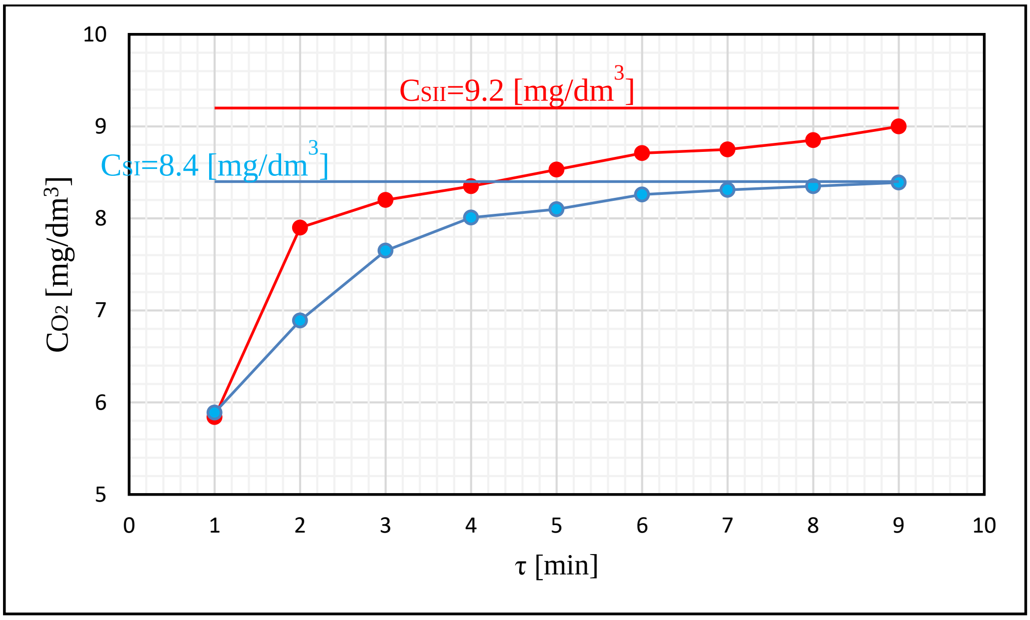

Fig. 9. Graphical representation of the function = f(τ) for version I curve 1 și and for version II curve 2
Blue curve: C= f(τ) for FBG with ø = 0.1 mm;
Red curve: C= f(τ) for FBG with ø = 0.05 mm.

Comparing the values of C mg / dm^3 in table 2 with those in table 3, one can observe that those in Table 3 are higher, so the aeration in version II is more efficient.

4. Conclusions

Any process of aeration of water aims at an increase in the content of the dissolved oxygen in the water.
This oxygen concentration must be maintained within normal limits, because its increase or decrease affects the quality of the water, so implicitly the existence of life forms in the water.
Tables 2 and 3 show the following values of the function C = f (τ):

- in table 2, the value of C tends to C_s after 105 min: 8.35 → 8.4 [mg / dm^3]
- in table 3, the value of C reaches the value of 8.35 [mg / dm^3] after a time of 45 min.

Therefore, the aeration process has a shorter duration by about 50%, i.e. the duration of the aeration process is reduced by half.

As a result, a sure way to improve the stagnation of stagnant water is to make fine bubbles generators to introduce air bubbles with a diameter as small as possible; this involves making plates with orifices as small as possible.

In the paper, a diameter of the orifices of 0.05 mm was reached, which the authors hope will be exceeded, tending to orifices of the order of nanometers.

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