Researches on Water Aeration Using Fine Bubbles Generators

PhD Std. **Marilena Monica BOLTINESCU (ROZA)**[1], Prof. Dr. Eng. **Nicolae BĂRAN**[1],
Dr. Eng. **Albertino Giovani ROZA**[1], Șl. Dr. Eng. **Mihaela CONSTANTIN**[1]*

[1] University Politehnica of Bucharest

* i.mihaelaconstantin@gmail.com

Abstract: *The paper presents the constructive solution of a fine air bubble generator that is used to aerate waters. This generator is provided with a perforated plate, which has orifices for the introduction of air into the water, as follows:*
- Variant I: the diameter of the orifice is 0.1 mm
- Variant II: the diameter of the orifice is 0.5 mm.
A computation program is being developed showing the change in the concentration of dissolved oxygen in the water as a function of time in which air is introduced into the water.
Theoretical and experimental data for the two variants are compared; it is concluded that as the diameter of the orifice in the perforated plate decreases, the water aeration process becomes more efficient.

Keywords: *Fine bubble generator, water aeration, dissolved oxygen, orifice.*

1. Introduction

The gaseous mixture that can be introduced into the water to increase the oxygen concentration can be [1] [2]:
1. atmospheric air (21% O_2 + 79% N_2);
2. atmospheric air + oxygen taken from a cylinder in certain proportions;
3. low nitrogen air supplied by oxygen concentrators.
In case 1 it can be stated that an aeration process takes place which aims at oxygenating the waters.
In cases 2 and 3, as the oxygen content of the gas mixture changes, the notion of water oxygenation is introduced, i.e., a distinction must be made as follows:
• water aeration takes place by introducing atmospheric air into the water (1);
• oxygenation of water takes place by introducing oxygen-enriched air (2) + (3)
Aeration and oxygenation of water are biphasic mass transfer processes, the gaseous phase passes into the liquid phase (water). Applications of these processes are used for the following purposes:
- for wastewater treatment;
- for biological wastewater treatment;
- when collecting and separating emulsified fats from wastewater;
- in maintaining an optimal level of oxygen concentration for underwater plants or animals;
- in some of the processes of treating the water captured from a source, to make it drinkable.
Gas bubbles immersed in water can be classified according to their diameter as follows (figure 1):

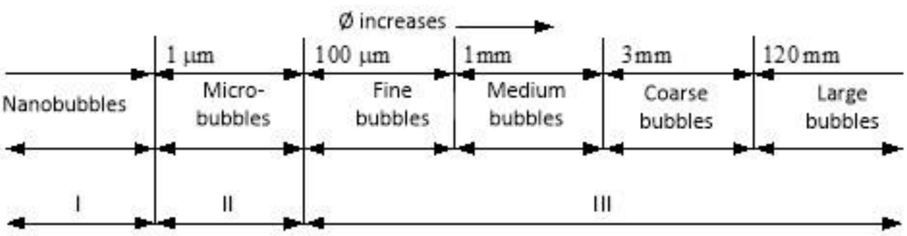

Fig. 1. Classification of gas bubbles according to their diameter (ø):
I - the area where the gas bubbles can be observed under the microscope;
II - the area where gas bubbles can be observed with difficulty;
III - the area where gas bubbles can be observed with the naked eye.

In figure 2, one can observe that the oxygen in the water appears in two forms:
• O_2 bound to H_2;
• Free O_2, called dissolved oxygen in water.

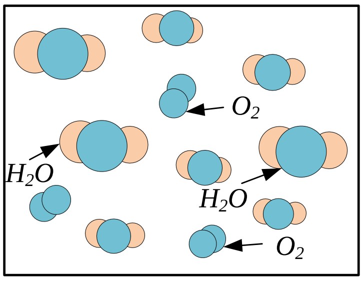

Fig. 2. Oxygen dissolved in water

The solubility of oxygen in water is dependent on temperature, atmospheric pressure, the size of the air-water contact surface and water turbulence. The oxygen needed for the aeration process is taken from the atmospheric air and introduced into the water by three methods: pneumatic, mechanical, and mixed. The pneumatic method uses aeration devices that introduce fine air bubbles into the water; these devices are classified into three categories, as follows [3] [4]:
I. fine bubble generators constructed of ceramic, plastic materials;
II. fine bubble generators constructed of perforated elastic membranes;
III. fine bubble generators with perforated plates made with the help of micro-machines for drilling in coordinates, with drills of ø <0.5mm.
Oxygen transfer in wastewater is an important issue in treatment technology; using fine bubble aeration, the amount of air introduced is optimized, obtaining significant energy savings. Fine air bubbles are obtained with the help of fine bubble generators (FBG) made of ceramic materials (porous diffusers) or perforated plates.
The use of porous diffusers has the following disadvantages:
• emitted air bubbles have unequal diameters;
• air bubbles appear irregularly, only on certain parts of the surface of the porous diffusers;
• porous diffusers have high pressure losses [5].
In recent years, researches on water oxygenation have focused on obtaining fine bubble generators whose orifices for the air introduction into the water have a diameter d <1 mm. FBGs were built which has the perforated plate made by an unconventional technological process (EDM); this process ensures a uniform distribution of the orifices on the surface of the plate and an equal diameter of the orifices. The size and dimension of the orifices are an important parameter of the FBG because it directly affects the air inlet pressure in the FBG, and the size of the air bubble blown into the water.

2. Mathematical model- the oxygen transfer rate equation

The rate of transfer of dissolved oxygen in water is given by the relation [6] [7]:

$$\frac{dC}{d\tau} = a \cdot k_L \cdot \left(C_s - C_0\right)\ [kg / m^3 s] \tag{1}$$

where:
dC / dτ - rate of change of dissolved oxygen concentration in water (rate of oxygen transfer to water);
ak_L - volumetric mass transfer coefficient [s^{-1}];
C_s - mass concentration of oxygen at saturation in the liquid phase [kg / m^3];
C - current mass oxygen concentration in the liquid phase [kg / m^3].
The term "ak^L" includes:
k_L- mass transfer coefficient [m / s];
a - specific interphase contact surface:

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

where: A- gas bubble area [m^2];
V - the volume of the biphasic system (air + water) [m^3];
If boundary conditions $C = C_0$ are imposed for $\tau = 0$, equation (1) can be integrated [8] [9] [10]:

$$\frac{dC}{C_s - C} = a \cdot k_L \, d\tau \tag{3}$$

In the hypothesis that $C < C_s$, after integration, it results:

$$-ln\left(C_s - C\right) = a \cdot k_L \cdot \tau + ct \tag{4}$$

The constant is obtained from the limit condition: $C = C_0$ for $\tau = 0$
and has the value:

$$ct = -ln\left(C_s - C_0\right) \tag{5}$$

Introducing (6) in (4) one can obtain:

$$-ln\left(C_s - C\right) = a \cdot k_L \cdot \tau - ln\left(C_s - C_0\right) \tag{6}$$

$$ln\left(C_s - C\right) = ln\left(C_s - C_0\right) - a \cdot k_L \cdot \tau \tag{7}$$

$$ln\left(C_s - C\right) = ln\left(C_s - C_0\right) + ln\, e^{-a \cdot k_L \cdot \tau} \tag{8}$$

$$ln\left(C_s - C\right) = ln(\left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau}$$

$$C_s - C = ln(\left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau}$$

$$C = C_s - \left(C_s - C_0\right) \cdot e^{-a \cdot k_L \cdot \tau} \tag{9}$$

τ=0

To determine theoretically the increase in the concentration of dissolved oxygen in water as a function of the oxygenation time of water, the following quantities must be known:

Table 1: Variation of saturation concentration with temperature at p_{atm} = 760 mm Hg

t°C	**Cs**	t°C	**Cs**	t°C	**Cs**	t°C	**Cs**
0.0	**14.60**	10.0	**11.30**	20.0	**9.10**	30.0	**7.50**
0.5	**14.40**	10.5	**11.10**	20.5	**9.00**	30.5	**7.50**
1.0	**14.20**	11.0	**11.00**	21.0	**8.90**	31.0	**7.40**
1.5	**14.00**	11.5	**10.90**	21.5	**8.80**	31.5	**7.30**
2.0	**13.80**	12.0	**10.80**	22.0	**8.70**	32.0	**7.30**
2.5	**13.60**	12.5	**10.60**	22.5	**8.60**	32.5	**7.20**
3.0	**13.40**	13.0	**10.50**	23.0	**8.60**	33.0	**7.20**
3.5	**13.30**	13.5	**10.40**	23.5	**8.50**	33.5	**7.10**
4.0	**13.10**	14.0	**10.30**	24.0	**8.40**	34.0	**7.00**
4.5	**12.90**	14.5	**10.20**	24.5	**8.30**	34.5	**7.00**
5.0	**12.70**	15.0	**10.10**	25.0	**8.20**	35.0	**6.90**
5.5	**12.60**	15.5	**10.00**	25.5	**8.20**	35.5	**6.90**
6.0	**12.40**	16.0	**9.80**	26.0	**8.10**	36.0	**6.80**
6.5	**12.30**	16.5	**9.70**	26.5	**8.00**	36.5	**6.80**
7.0	**12.10**	17.0	**9.60**	27.0	**7.90**	37.0	**6.70**
7.5	**12.00**	17.5	**9.50**	27.5	**7.90**	37.5	**6.70**
8.0	**11.80**	18.0	**9.40**	28.0	**7.80**	38.0	**6.60**
8.5	**11.70**	18.5	**9.30**	28.5	**7.70**	38.5	**6.60**
9.0	**11.50**	19.0	**9.30**	29.0	**7.70**	39.0	**6.50**
9.5	**11.40**	19.5	**9.20**	29.5	**7.60**	39.5	**6.50**

a) Initial oxygen concentration for a given water temperature (t = 25 ° C), $C_0 = 5.12$ mg / dm^3;
b) The saturation concentration $C_s = 8.2$ mg / dm^3 for the same water temperature t = 25 ° C can be read from Table 1 [11].
c) Integration step: a research duration of about two hours is estimated; the step: h = 1 min is chosen (n = 121); =τ = 120 min.
From the literature [12] [13], for a constant airflow of 540 dm^3 / h, a value for ak_L of 0.09 is adopted.

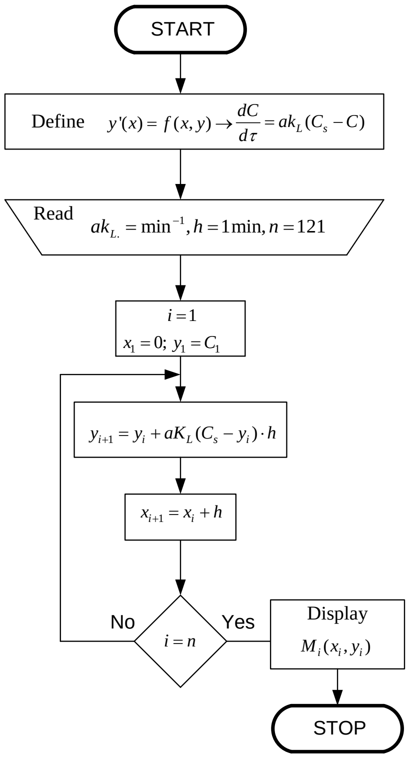

Fig. 3. Logical computation scheme for the numerical integration of the differential equation of the oxygen transfer rate

The scheme (figure 3) is based on the Euler method, the method with separate steps and explicit algorithm [14] [15].

2.1. Establishing the architecture of the orifice plate of the fine air bubbles generator

Two categories of parameters intervene in the water oxygenation process:
I. geometric parameters of the fine bubble generator, more precisely of the plate with fine orifices (D, s, d_o, d); (figure 4).
II. operating parameters ($\dot{V}$, Δp_{FBG}, H, C_0).
Notations:
D - the diameter of the bubble at its detachment from the orifice [m];
s - thickness of the perforated plate [m];
d_o – orifice diameter [m];
d - the distance between two orifices on the same line [m].

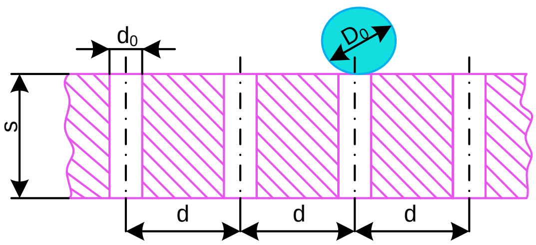

Fig. 4. Logical computation scheme for the numerical integration

In the design and construction of the FBG, the following two conditions must be met: [16] [17]:

$$I - \quad \frac{s}{d_0} > 3, \tag{10}$$

$$II - \quad \frac{d}{d_0} > 8 \tag{11}$$

In the experimental researches for the two variants are obtained:

$$I - \; d_0 = 0.1 mm;\; s / d_0 = 2 / 0.1 = 20;\; d / d_0 = 2 / 0.1 = 20 \tag{12}$$

$$II - \; d_0 = 0.5 mm;\; s / d_0 = 2 / 0.5 = 4;\; d / d_0 = 10 / 0.5 = 20 \tag{13}$$

One can observe that for the two variants the ratio s / d_0> 3, and the ratio d / d_0 = 20, so d / d_0> 8.
From the previous researches and considering the architecture of the installation for experimental research on FBG, an outlet air section in water of A = $1.2 \cdot 10^{-6} m^2$ was chosen.
The number of orifices for the two variants results:

$$I - \; d_0 = 0.1 mm;\; n_{0.1} = \frac{A}{\left(\pi \cdot d_0^2\right)/4} = \frac{1.2 \cdot 10^{-6}}{\frac{\pi \cdot \left(0.1 \cdot 10^{-3}\right)^2}{4}} = 152\, orifices \tag{14}$$

$$I - \; d_0 = 0.5 mm;\; n_{0.5} = \frac{A}{\left(\pi \cdot d_0^2\right)/4} = \frac{1.2 \cdot 10^{-6}}{\frac{\pi \cdot \left(0.5 \cdot 10^{-3}\right)^2}{4}} = 6\, orifices \tag{15}$$

A new generation of FBG is proposed in which the air dispersion orifices in the water are processed by micro-drilling, and the diameters of the orifices are of the dimensions: d_{0I} = 0.1 mm, d_{0II} = 0.5 mm.
Other types of FBG obtained by unconventional technologies are presented in the papers [18] [19].
The following are the two constructive variants of FBG, namely:
Variant I: FBG with a perforated plate with 152 orifices, ø 0.1 mm;
Variant II: FBG with a perforated plate with 6 orifices, ø 0.5 mm.
I. FBG presentation for variant I.
Figure 5 shows the plate with orifices.

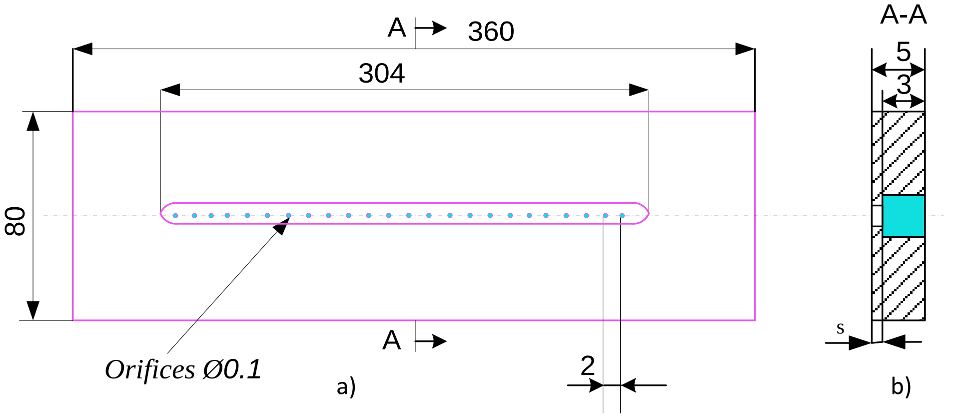

Fig. 5. FBG orifices plate
a) plan view; b) cross section

To perform the orifices in the plate (figure 5), an alveolus (a channel) 3 mm deep and 304 mm long was created. Subsequently, with the help of a C.N.C (numerically controlled machine), a special machine for microprocessors type KERN Micro 152 orifices were made in channel with Ø 0.1 mm. This machine has an accuracy of ± 0.5 µm, which ensured the creation of a FBG which is an original construction solution.
Figure 6 shows the constructive solution of the FBG for variant I.

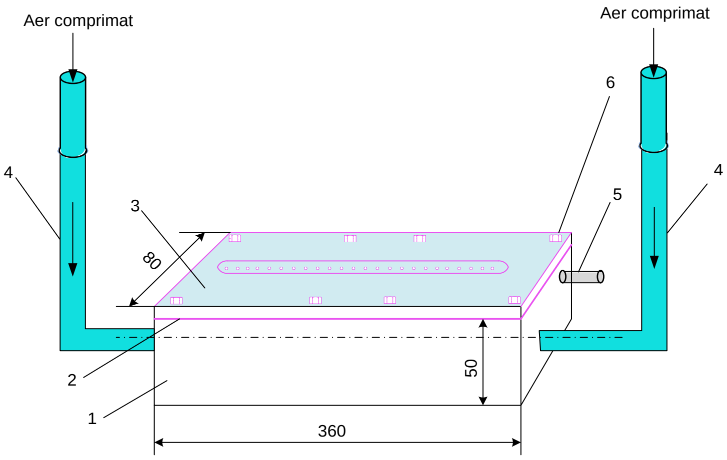

Fig. 6. Fine air bubble generator
1- compressed air tank; 2- sealing gasket; 3- plate with orifices; 4- FBG Ø 18mm compressed air supply pipe; 5-connection for measuring compressed air pressure; 6- screws for fixing the plate with orifices in the tank frame

Following the running of the computation program, for the FBG in variant I the curve C = f (τ) presented in figure 7 was constructed (Initial data: $\dot{V} = 600\, dm^3 / h$; C_0 = 5.48 mg / dm^3, τ = 120 minutes; $t_{H_2O} = 24\,^{\circ}C$; C_s = 8.4 mg / dm^3).

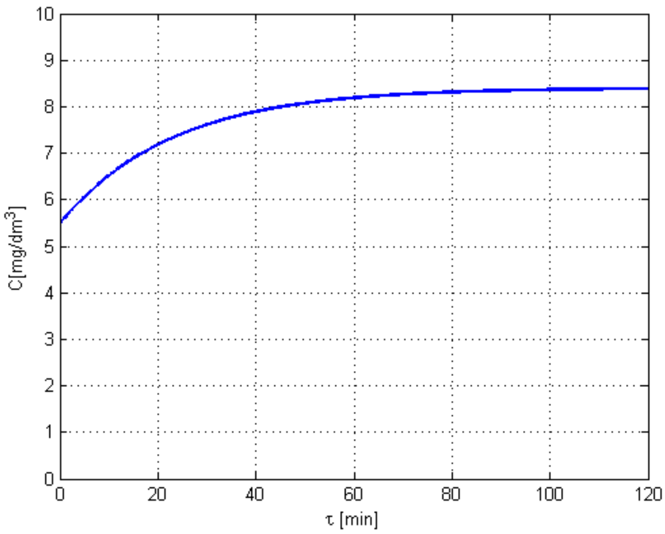

Fig. 7. Variation of the dissolved O_2 concentration in water as a function of time for FBG in variant I with ø 0.1 mm

II. FBG presentation for variant II.
A rectangular plate is chosen as the construction form for the orifice plate. A sketch of this plate is shown in Figure 8:

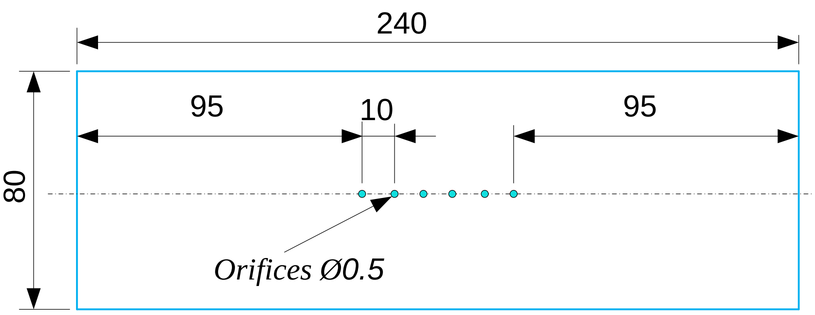

Fig. 8. Perforated plate with 6 orifices of Ø 0.5 mm

For this variant, the distance between the orifices is 10 mm and the thickness of the aluminum plate is 2 mm. The variation of the dissolved O_2 concentration in time for FBG in variant II is shown in figure 9.

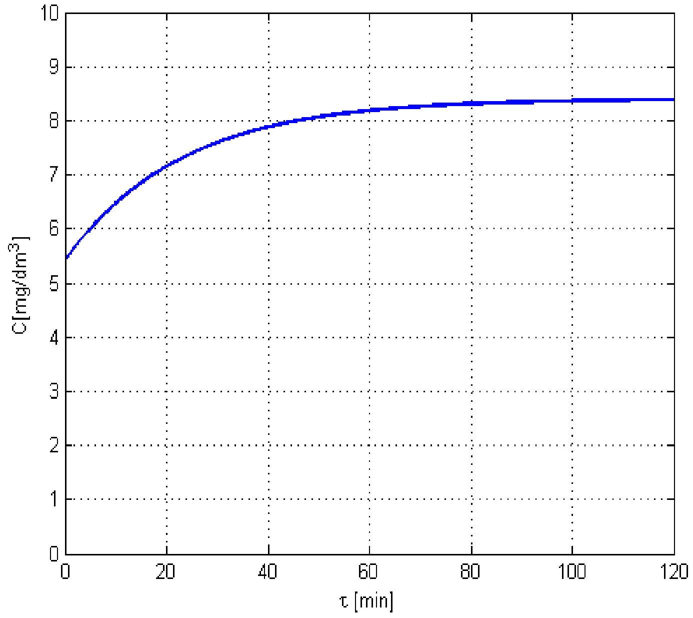

Fig. 9. Variation of the dissolved O_2 concentration in water as a function of time for FBG in variant II with ø 0.5 mm

To highlight the influence of the diameter of the air introducing orifice in the water on the concentration of dissolved oxygen, a comparison of the theoretical researches carried out for the two types of fine bubble generators was made.

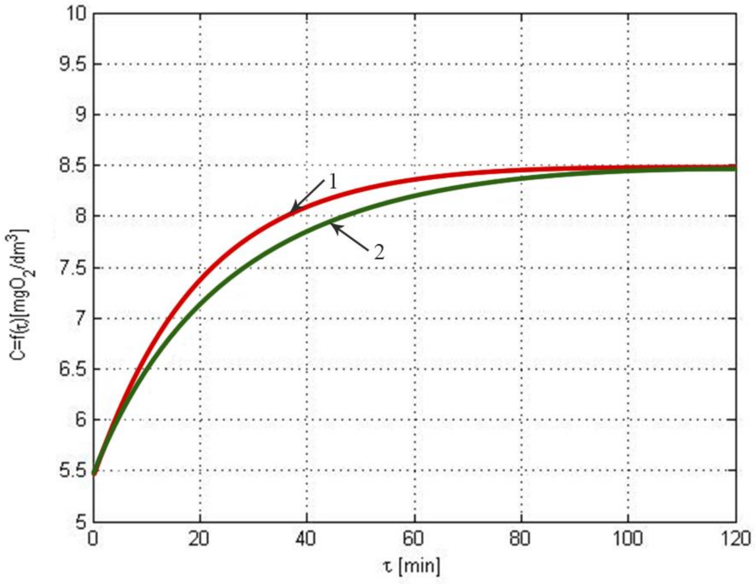

Fig. 10. Variation in the dissolved O_2 concentration in water as a function of time
1- FBG in variant I (Ø 0.1 mm), 2 - FBG in variant II (Ø 0.5 mm)

Analyzing figure 10, the following conclusions can be drawn:
- the increase of the dissolved oxygen concentration in the water is faster in the case of the fine bubble generator with orifices Ø 0.1 mm compared to the generator of fine bubbles with orifices Ø 0.5 mm.
- it is confirmed that a smaller diameter of the air introducing orifices in the water leads to a more efficient oxygenation of the water volume.

2.2. Presentation of the experimental installation

The scheme of the experimental installation corresponding to variants I and II, is presented in figure 11 [20] [21].

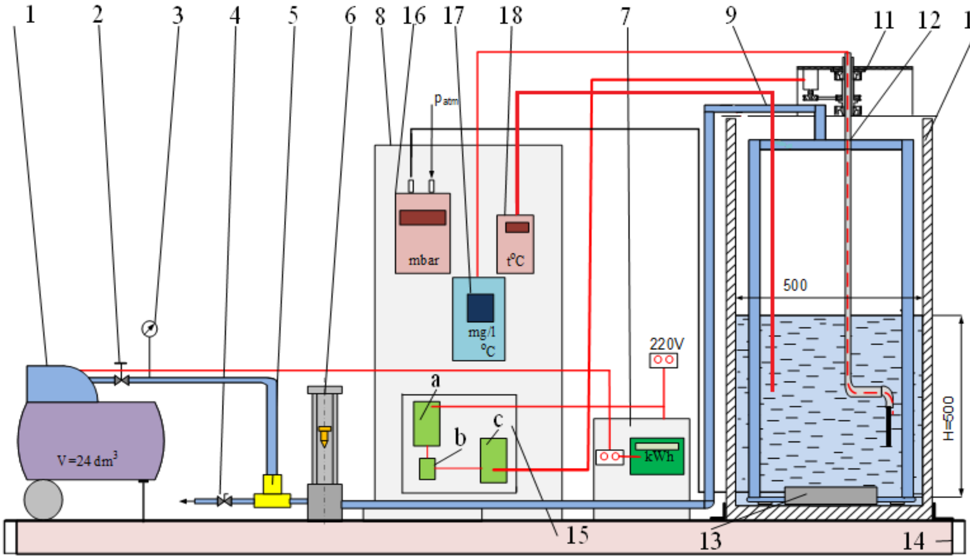

Fig. 11. The scheme of the experimental installation for researches on water oxygenation by introducing compressed atmospheric air into the water tank
1 - electro compressor with air tank; 2 - pressure reducer; 3 - manometer; 4 - connection for evacuating air into the atmosphere; 5 – T-joint; 6 - rotameter; 7 - electrical panel; 8 - panel with measuring devices; 9 - pipe for transporting compressed air to the bubble generator, 10 - water tank; 11 - mechanism of actuation of the probe; 12 - oxygenometer probe; 13 - bubble generator; 14 - support for installation; 15 - control electronics: a - power supply, b - switch, c - control element, 16 - digital manometer; 17 - oxygenometer; 18 - digital thermometer

In variant I, the compressed air supplied by a compressor (1) passes through a rotameter (6) so that through the pipe (9) it reaches the FBG (13).

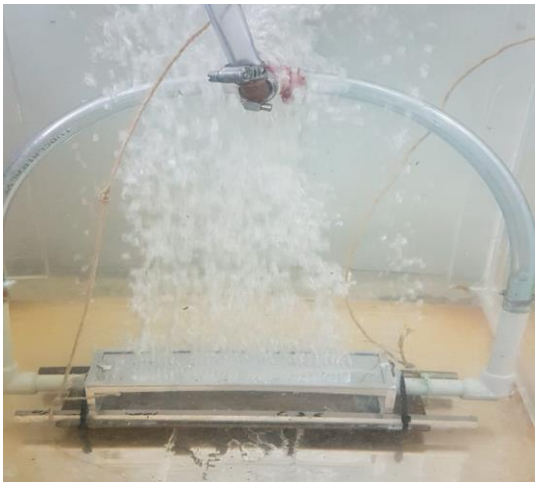

Fig. 12. Bubble curtain emitted by the fine bubble generator in operation

Figure 12 shows the bubble curtain emitted by FBG inserted in the water tank

3. Results and discussion

During the experimental researches on the operation of FBG in the two variants, the following remained constant: the area of the air outlet section in the water and the height of the water layer above the FBG (hydrostatic load).

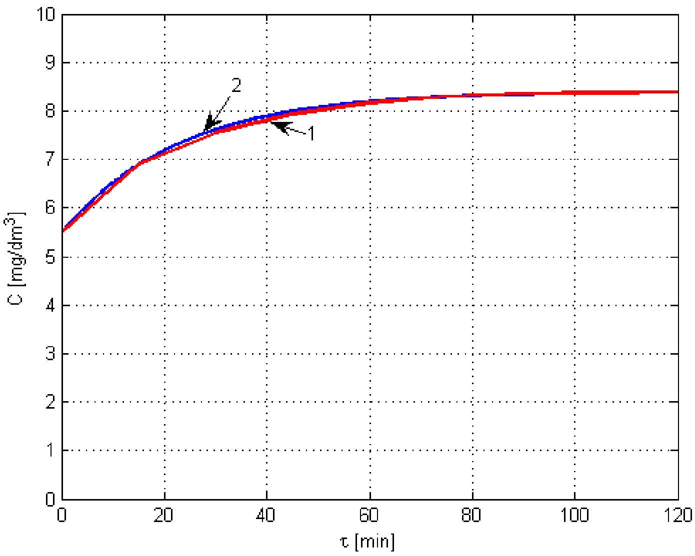

Fig. 13. Variation of the dissolved O_2 concentration in water as a function of time: C = f (τ)
1- theoretical results in the case of FBG with Ø 0.1 mm; 2-values measured in the case of FBG with Ø 0.1 mm

The experimental and theoretical curves are close, which means that the measurements are correct, confirming the superior capabilities of the oxygenation system.
Similar to the fine bubble generator with 152 orifices Ø 0.1 mm and for the fine bubble generator with 6 orifices Ø 0.5 mm the curves in figure 14 are obtained.

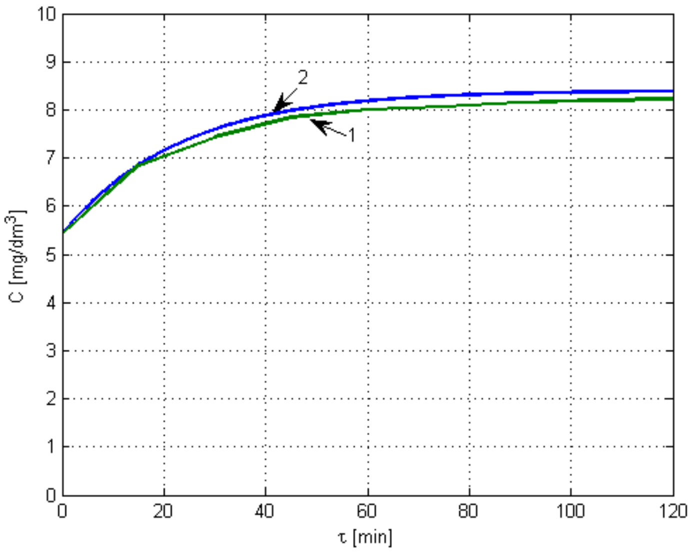

Fig. 14. Variation of the dissolved O_2 concentration in water as a function of time: C = f (τ)
1- theoretical results in the case of FBG with Ø 0.5 mm; 2-values measured in the case of FBG with Ø 0.5 mm

The experimentally determined values were graphically represented by the curves C = f (τ) (figure 15).

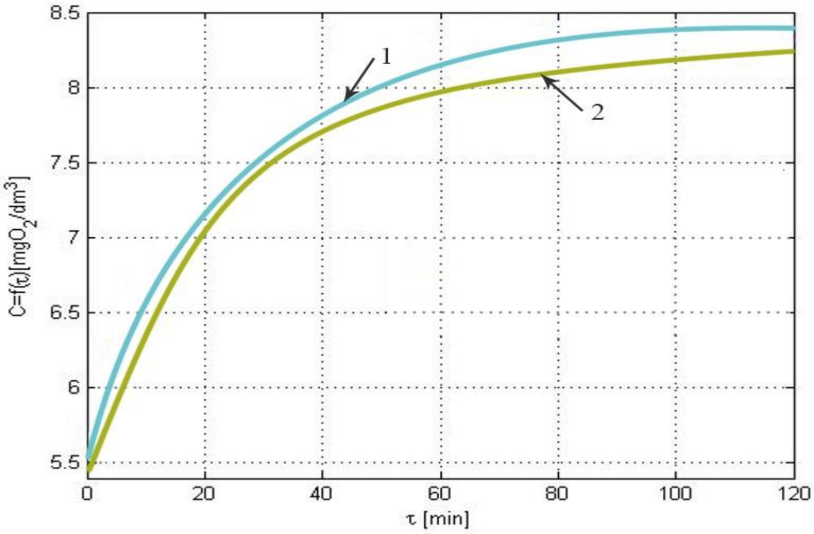

Fig. 15. Variation of the dissolved O2 concentration in water as a function of time: C = f (τ)
Measured values for variant I
Measured values for variant II

Figure 15 shows that variant I (curve 1) is more advantageous.

4. Conclusions

Aeration is necessary to improve water quality, to avoid the occurrence of oxygen deficiency in systems where there is a biochemical consumption of oxygen above the self-aeration capacity of water, to eliminate toxic gases that can be found in water and in the water treatment process.
The main purpose of water aeration, regardless of the industry and the reason for its use, is to increase or maintain an optimal level of dissolved oxygen in a water mass. The oxygen needed for the aeration process is taken from the atmospheric air and introduced into the water. For this aeration to be effective, a uniform dispersion of air in the volume of water must be ensured.
The pressurized air is dispersed in the form of bubbles by a specialized equipment, located at the bottom of the treatment tank.
So, the main purpose of aeration regardless of the industry and the purpose where it is used is to increase or maintain a high or optimal level of dissolved oxygen in a water mass to be used for various purposes or reintroduced into its natural circuit. The aeration process is used in the treatment and improvement of water quality, but also in many other fields including medicine, agriculture, fish farming, etc.

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